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New Mexico Journal of Science

WATER RESOURCES ISSUES IN NEW MEXICO

Esteban A. Herrera
Thomas G. Bahr
Catherine T. Ortega Klett
Bobby J. Creel
Editors

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Approximately 90% of New Mexicans depend on groundwater for their drinking water. About 1.45 million acres are dedicated to irrigated cropland. Of that, about 1 million acres are planted with crops and irrigated in any given year. Without a doubt groundwater is the state's most valuable, long-term natural resource. New Mexico's social and economic development depends highly on the availability of groundwater.

There have always been legal issues involving water in the state, from the acequias in northern New Mexico to the Elephant Butte Irrigation District in the south. New Mexico's water contamination also is a growing concern. The biggest source of contamination is household septic tank systems, followed by oil and gas production activities and underground storage tanks. To date, little is known about the effects of agricultural activities, but there is concern about the possibility of nitrates (from the use of nitrogen fertilizer) leaching into groundwater sources. It also is generally thought that New Mexico does not have nor is expected to have a pesticide/groundwater problem because of the relatively low volume (and type) of soil-applied insecticides, that are used and the trend away from this practice.

Luckily, New Mexico is recognized as a leader in the development of programs to address water issues. Because water has always been an important concern, our water laws and information about water are more advanced than in many eastern states. In fact, information about groundwater aquifers and water quality and other data necessary for a given groundwater plan has always been available. Regulations and procedures as well as statutory authority also are in place.

A big part of New Mexico's land is located in a semiarid area, making water a precious commodity. It will become even more important in the years to come. As time goes on, the state's population will undoubtedly grow, significantly increasing the use of water around the metropolitan areas. (Early in this century one out of two people lived in a rural community). As the number of industries increase so will water needs. It is not a distant possibility that agricultural water needs will be challenged and farmers will have to be more discriminating about the crops they grow. Also, they will need to become highly efficient at managing the water.

However, agriculture alone should not bear the burden of water conservation and efficient water management. New Mexico's industry owners and citizens also will have to learn (or be forced) to be more conscientious about daily water use. In the desert, our lives converge around water, and we need to share it the best we can.

In this issue, an attempt was made to cover many aspects of the complex and controversial water issues facing New Mexico.

This year, we are lucky to have recruited Dr. Tom Bahr, Director of the Water Resources Research Institute and his staff at New Mexico State University in Las Cruces to co-edit for the 1998 Journal issue. His experience with New Mexico's water resources as well as his professionalism, proved to be invaluable for coordinating and enlisting an excellent group of authors with ample experience with the state's water issues.

Esteban A. Herrera, Editor
New Mexico Journal of Science
Extension Horticulturist
New Mexico State University
Las Cruces, NM 88003

NEW MEXICO ACADEMY OF SCIENCE MISSION STATEMENT

The *New Mexico Journal of Science* is published yearly with each issue devoted to a different theme. The *Journal* has been published since 1960.

The goals of the New Mexico Academy of Science are: to promote science and science education within the state of New Mexico; to improve communication among scientists, science educators, and the New Mexico general public and its governmental representatives; recognize scientists, science educators, and science students; to encourage scientific research and increase public awareness of science's role in human progress and welfare.

The New Mexico Academy of Science is a member of the National Association of Academies of Science (NAAS) and an affiliate of the American Association for the Advancement of Science (AAAS). The Academy, founded in 1902, has been in continuous existence since 1915.

Membership in the New Mexico Academy of Science is open to any person or organization engaged in or interested in promoting science in the state of New Mexico.

The New Mexico Academy of Science sponsors and administers several programs to accomplish its goals. These projects include the Visiting Scientist Program, the Junior Academy of Science, the Outstanding Teacher Award Program, and the annual *Journal of Science.*

The Academy hosts an annual meeting with speakers, panelists, exhibitors, and scientific presentations for the professional and lay community in New Mexico. The New Mexico Museum of Natural History and Science is a collaborative partner for this event.

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c/o New Mexico Museum of Natural History and Science
1801 Mountain Road, NW
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NEW MEXICO ACADEMY OF SCIENCE

The New Mexico Academy of Science was founded in 1902 and has been formally affiliated with the New Mexico Museum of Natural History and Science since 1995. The Academy's mission is to foster scientific research and scientific cooperation, increase public awareness of the role of science in human progress and welfare, and to promote science education in New Mexico. Our annual journal is an important activity in fulfilling this mission.

The Academy has published the *New Mexico Journal of Science* since 1960. Each annual issue is a topical collection on a subject of particular importance to New Mexico, such as this year's intriguing and controversial subject — water resources in New Mexico. The following subtitles indicate several recent topics of our journals:

Environmental Management Need in New Mexico: *Current and Future Needs (1997)*
New Mexico's Natural Heritage: *Biological Diversity in the Land of Enchantment (1996)*
Astronomy in New Mexico: *Past, Present and Future (1995)*
The Importance of Agricultural Science in New Mexico's Economy (1994)

This year's Journal, as well as several in the past (including the titles above), has been edited by Dr. Esteban A. Herrera of New Mexico State University. The New Mexico Academy of Science is indeed grateful to Dr. Herrera for the excellent quality of these publications and for his stewardship of our Journal in recent years.

The Academy distributes the *New Mexico Journal of Science* and four newsletters to its members during the year. Membership is open to anyone interested in science. Beginning this year, information on the Academy may also be obtained through our web site at www.nmas.org.

In addition to its journal, newsletter and our annual banquet, the Academy offers several other programs and activities. Through the Visiting Scientist Program, educators can invite scientists to speak in junior and senior high classrooms. In the Junior Academy, students in the junior and senior divisions participate in an annual science paper competition. In the Teacher Awards Program, we select two outstanding New Mexico science teachers each year and present them with awards at our annual banquet in November. The Academy is a member of the National Association of Academies of Science and an affiliate of the American Association for the Advancement of Science (AAAS).

Richard E. Nygren, 1998 President
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PREFACE

Tom Bahr[1]

Since its establishment in 1963, the New Mexico Water Resources Research Institute (WRRI), located on the New Mexico State University campus, has been the statewide nucleus for coordinating water resources research. During the past three decades the WRRI has administered over 300 research and educational projects focused on solving the many critical water problems facing New Mexico as well as regional and national water problems. The WRRI is pleased to sponsor the 38th volume of the *New Mexico Journal of Science* which focuses on the intricacies of current water issues in New Mexico.

Many of the papers contained in this volume represent research results of projects funded through the WRRI. In addition to providing funding for New Mexico faculty and students involved in water research, the Institute cooperates closely with the water community of New Mexico including federal, state and local water agencies, water policy makers, private business water concerns, water users such as farmers, and legal entities. Papers appearing in this volume were written by authors with whom the WRRI has developed a close working relationship.

The WRRI funds basic and applied research and educational projects in a variety of disciplines including agriculture, economics, management, nearly all branches of engineering, hydrology, water law, and the physical and biological sciences. The Institute keeps the citizens of New Mexico informed of its research results through its publication series, newsletters, conferences, presentations, homepage on the Internet and special publications such as the *New Mexico Journal of Science.*

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[1] Director, New Mexico Water Resources Research Institute, New Mexico State University, Las Cruces, NM 88003, e-mail: tbahr@wrri.nmsu.edu

In the arid southwest, we are reminded daily of the importance that water plays in all our lives. It is a finite resource with an ever increasing population depending on it. We must develop accurate scientific information about the nature and extent of our water resources, and have an informed citizenry on the water problems facing our state if we are to make sound management decisions concerning its future use. Hopefully, the manuscripts contained in this volume will help educate its readers on a broad spectrum of water issues. We thank the authors who contributed their work for this issue and acknowledge their commitment to solving the critical water problems facing New Mexico.

AN OVERVIEW OF NEW MEXICO'S WATER RESOURCES

Tom Bahr[2]

ABSTRACT

Surface water supplies in New Mexico are scarce and for practical purposes fully appropriated. This means there will be few, if any, new appropriations of water in the future. In all likelihood, new uses will have to be accommodated by water transfers from existing uses. Fresh groundwater supplies are being seriously depleted in many parts of the state and new appropriations are likely to be conditioned on the retirement of surface water rights where ground and surface water supplies are hydrologically connected. It is not likely that New Mexico will discover any new water sources to augment the present supply. Agriculture annually accounts for well over 80 percent of the water consumed in the state. Because of the potential for large savings, water conservation in the agricultural sector is receiving increased attention but because of the complexity of this subject, it is little understood by the general population and policy makers. New Mexico has developed a comprehensive body of water law which has guided the orderly development of its water resources since territorial days. These laws and their administration have served the state well for 90 years and they provide a solid base for shaping New Mexico's water future.

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[2] Director, New Mexico Water Resources Research Institute, New Mexico State University, Las Cruces, NM 88003, e-mail: tbahr@wrri.nmsu.edu

INTRODUCTION

The following discussion is an attempt to condense a vast amount of information on New Mexico's water supply, water use, water law and water administration into less than 35 pages. In dealing with a subject as complex as water resources it is easy to get bogged down in technical details and lose sight of the big picture. It is not only important for the general public and policy makers to become informed about New Mexico's water resources, it is essential for academicians not to lose sight of the big picture so they may better appreciate how to relate and focus their present and future research into the solution of important water problems. The purpose of this introductory chapter is to attempt to provide such a framework.

OVERVIEW OF NEW MEXICO'S WATER SUPPLY

On the average, New Mexico receives about 14 inches of precipitation a year, making it the third most arid state in the nation. Some regions receive only half that amount, while higher elevations in the northern mountains receive over 30 inches, mainly as snow (Figure 1). In all areas of the state, the annual open-pan evaporation exceeds precipitation, in some cases by over 100 inches (NMWRRI, 1988).

Of the five main rivers in the state, two flow westward and three flow southeasterly. The largest, the Rio Grande, travels some 1,800 miles from its source in Colorado before emptying into the Gulf of Mexico. Most of the state's small streams flow intermittently, except in mountainous areas and most New Mexico streams have high variability in flow.

Precipitation, in addition to rivers flowing into the state, amounts to approximately 84.4 million acre-feet of water per year. Unfortunately, about 97 percent of this supply evaporates. Water flowing out of state along with miscellaneous losses leaves a net of 1.2 million acre-feet of usable surface water. It is important to recognize that New Mexico

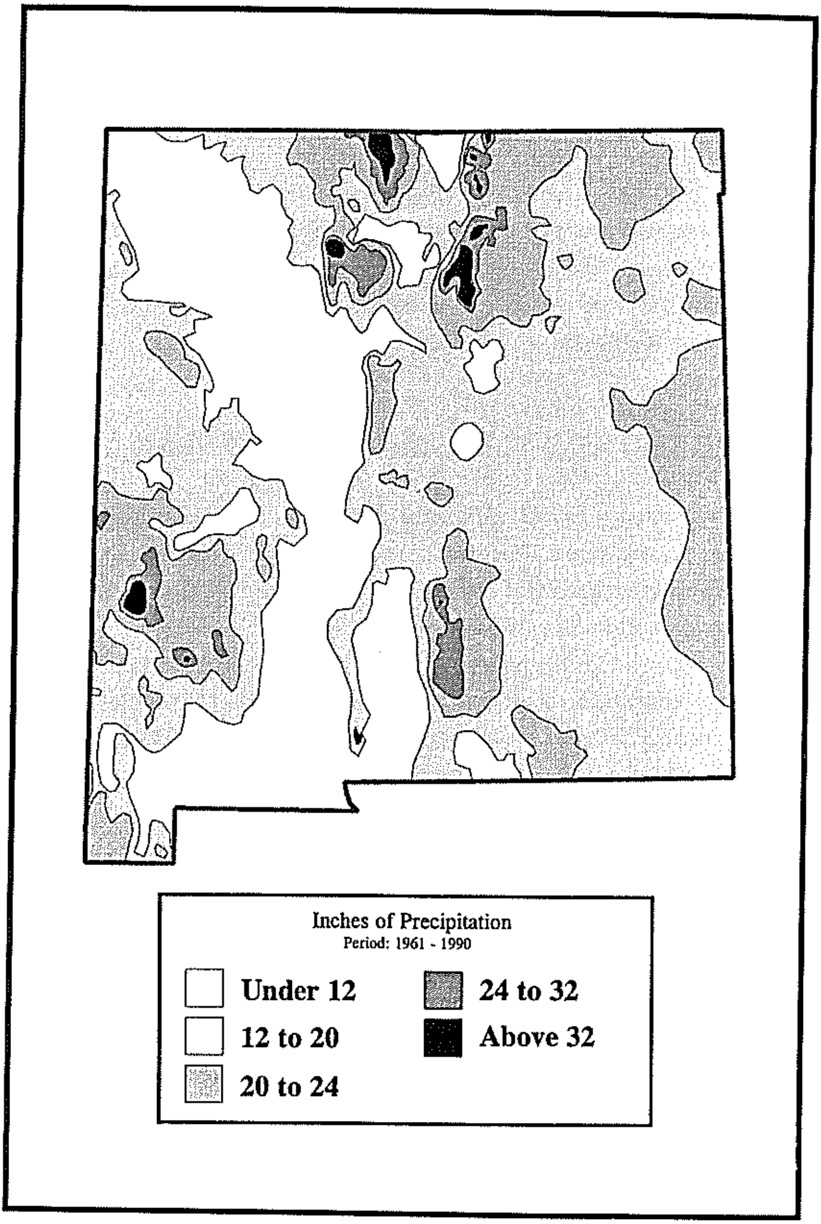


Figure 1. Average Annual Precipitation for New Mexico.

must share the surface water with neighboring states according to the terms of interstate compacts and court decrees. Most of New Mexico's surface water supplies are also fully appropriated, meaning that available water has been allocated to prior users. Most of this is dedicated to agricultural uses.

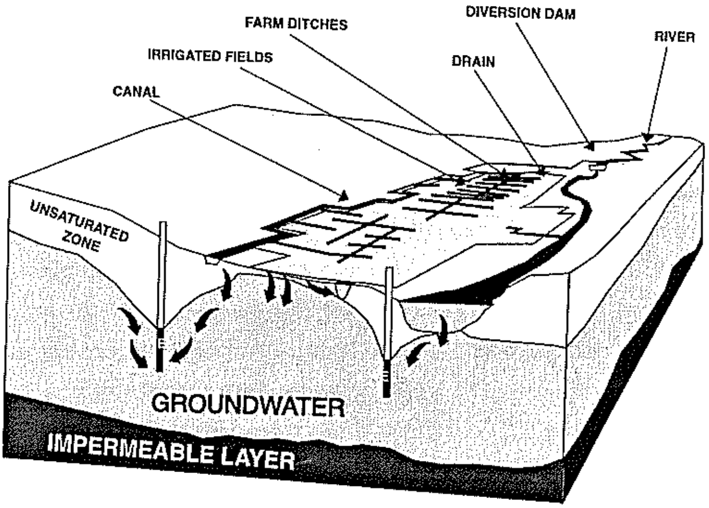
New Mexico's underground water supply is estimated at 20 billion acre-feet, enough to cover the entire state to a depth of about 260 feet. However, most of this water is saline or otherwise not suitable for public use. Only about 3 billion acre-feet is potentially recoverable fresh water (USGS, 1984).

GROUND AND SURFACE WATER INTERACTIONS

If water occurred in only one form, as a solid, divisible substance, it could be parceled and allocated in physical pieces. As a resource, however, water is not readily severable from all the institutions affected by decisions allocating it from one use to another. It is a changeable, mobile material in a natural system, the laws of which are imperfectly understood. Moreover, what is understood about hydrologic systems complicates rather than simplifies the task of allocating water. We now know, for example, that certain aquifers are connected to surface streams and that certain others are not. Most are partially connected and the degree of connection is critically important to water management decisions.

Water from various sources percolates down through the soil to fill aquifers, and, moving laterally underground, can eventually enter streambeds as recharge. Over time, because water pumped from an aquifer can be lost to the surface-stream recharge process, withdrawals from the aquifer will not only drain the aquifer itself but can also deplete the associated streams. Thus, where aquifers and surface streams are effectively the same water source, administration of them must recognize that fact. This is one of the most important issues facing water administrators.

Figure 2 shows a cross section of a typical irrigated river valley with such features as a diversion dam, canals, farm ditches, irrigated fields and drains. Wells for supplemental irrigation or municipal supplies create cones of depression in the water table as groundwater moves from the aquifer to the well. If the level of the groundwater should eventually drop in the vicinity of the river, water from the river will tend to percolate more rapidly into the surrounding soils than when the groundwater level was closer to the river. Flow in the river would thus be reduced by the amount of additional water which seeped through the bed of the river into the ground. If cones of depression



- WATER GAIN OR LOSS FROM RIVER?
- AMOUNT OF CANAL SEEPAGE?
- RECHARGE FROM IRRIGATED FIELDS?
- GROUNDWATER IN STORAGE?
- WELL PUMPING EFFECTS ON RIVER?
- SOURCES OF CONTAMINATION?

Figure 2. Interaction of Ground and Surface Water. Listed are Some Important Hydrological Questions.

from deep wells should intersect shallow wells, the shallow well could become dry. These systems are complex and depend on answers to a number of hydrological questions.

The rate at which groundwater pumping affects associated streams varies with the composition of the geologic zones separating the well from the stream. Usually, however, the rate is slow. One can take stream-related groundwater today and postpone dealing with the impact until far into the future. If one were to place a well directly into the river, the drawdown effect would be immediate and evident. But the impact on the river of wells fifteen miles away from the river might not be felt for a hundred years. Thus, although the impact eventually will be felt, until it is felt, water pumped from the well can be considered as withdrawal from storage rather than withdrawal from the river.

These temporal and spatial considerations are of great practical importance to municipalities because New Mexico municipalities rarely depend on surface water alone. In virtually every municipality in New Mexico, groundwater in storage which is hydrologically connected to surface supplies is a major water source. Accordingly, cities attempting to coordinate economic growth and water withdrawals have found it expedient to place wells as far from the river as possible and use the often high-quality groundwater to support domestic and industrial needs. In these cases, water from the city's wells is thought of as if it were drawn from a source independent of the river when, in fact, it is an interest-free loan from the river. Once created, however, the debt to the river eventually must be paid.

Water Quality

In many areas of New Mexico, groundwater is the only source of supply and is used by more than 90 percent of all public drinking water suppliers. In addition to the estimated 3 billion acre-feet of recoverable fresh water, another 1.4 billion acre-feet is only slightly saline water (1,000 to 3,000 mg/L TDS). While much of the state's usable groundwater is of good quality, there are some concerns with respect to recharge by irrigation return flows and by salt water intrusion. Irrigation return flows can carry essentially all of the dissolved salts in the original irrigation water supply. Percolation of these residual waters to the shallow aquifer eventually can lead to degradation of the groundwater quality.

In some areas of the state, such as in the Southwest Closed Basin and the Ogallala region on the east side of the state, the amount of water used each year greatly exceeds the recharge. This results in declining groundwater levels. As wells in these aquifers are pumped, they become more vulnerable to salt water intrusion from nearby saline zones in other aquifers. As the water level of a fresh water well is lowered, the saline water from surrounding aquifers tends to migrate toward the higher quality well.

Surface Water Quality

For the most part, the quality of the water in New Mexico's rivers is quite good, particularly in the upper reaches of stream systems. This is true for both organic and inorganic pollutants. Salinity, or the concentration of dissolved salts in water, is generally not a problem for agricultural use until the concentration becomes greater than about 1,000 mg/L. Salinity resulting from irrigation return flow, plus that contributed by municipal wastewaters, causes the TDS content of New Mexico's streams to increase downstream. It is important to recognize, however, that both New Mexico's Water Quality Act and the Federal Clean Water Act recognize irrigation return-flows as a reasonable consequence of the process of water use and they are not subject to regulation as a source of pollution under normal circumstances.

The salinity of the surface flow in many New Mexico streams is also a function of the rate of flow. During periods of flood flow or of snow melt, water quality is quite good and the dissolved solids content low. At low flows, a greater percentage of the base flow comes from municipal and agricultural return flows and groundwater discharge into the stream. While the volume can be small, the salinity can be significantly elevated.

Erosion from the land is a problem both in New Mexico and throughout the West despite the efforts made over the past 30 years to control this loss of resource. While some soil erosion is the result of wind action, water transport eventually takes place. Sediments have multiple effects on stream quality and on the uses of water. Sediment causes turbidity and can impair fish habitat of many rivers and lakes. Sediments also preclude some recreational activities.

Sediment is detrimental to irrigated agriculture and it reduces the storage capacity of reservoirs. For example, half of the storage capacity of Elephant Butte Reservoir has been lost since the dam was built in 1916. A few watersheds in New Mexico generate relatively large amounts of sediment per square mile of drainage area. These include the Rio Puerco, the Rio San Jose and the Rio Salado, which are all tributaries of the Rio Grande entering from the west between Albuquerque and Socorro. These drainages yield more than 1,000 tons of sediment per year per square mile of drainage area. Other tributaries of the Rio Grande that produce similar quantities of sediment annually are the Rio Chama, the Galisteo and the Jemez.

Some examples of clearer streams that carry very little sediment are the Gila River (65 tons per square mile per year) and the Rio Grande where it enters the state from Colorado (5 tons per year per square mile). The nature of the stream-flow (thunderstorm runoff versus snow melt) and vegetation on the watershed appears to account for the major differences but soil types must also play an important role.

The amount of sediment carried by a stream system varies from year to year depending on the intensity of rainfall and the antecedent conditions in the drainage area. For example, during the drought years of the middle 1950s, there was relatively little rainfall and runoff in many of New Mexico's streams. Some of the largest sediment yields on record followed this period when heavier runoffs occurred in 1957 and 1958. This was true for the San Juan, Rio Grande and Mora rivers (Harris, 1984).

WATER USE

The term "water use" as used here refers to water actually consumed or depleted and not to the total amount of water diverted from a stream system or water pumped from a well. Some diverted water may actually make its way back into a stream system or recharge an underground water supply. Consumed or depleted water is that amount used and not returned to the surface or groundwater system. The water use values used in this section are 1995 figures obtained from the State Engineer Office and are the most recent available (Wilson, 1997).

Consumptive water use in 1995 totaled 2.757 million acre-feet with slightly under half of this amount consisting of groundwater sources. About 87 percent of this water use was for irrigated agriculture and the associated evaporation losses from reservoirs which store irrigation water. In any given year, more water evaporates from New Mexico reservoirs than water consumption by all other non-agricultural uses in the state combined. Figure 3 shows a series of bar graphs which illustrate the 20-year trend in water use for all uses, agricultural uses and municipal uses.

As one would expect, water use varies between different regions of the state. New Mexico is subdivided into six major hydrological areas or basins. The largest of these hydrological basins is the Rio Grande in terms of area, population and water use. Figure 4 shows the surface

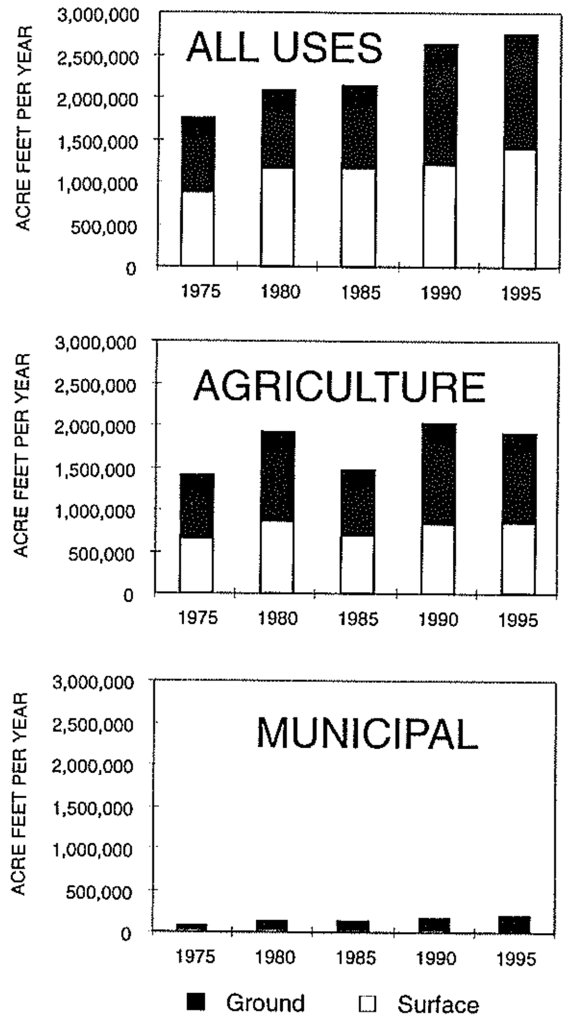


Figure 3. Statewide Surface and Groundwater Consumption from 1975 to 1995 for Selected Water Use Categories

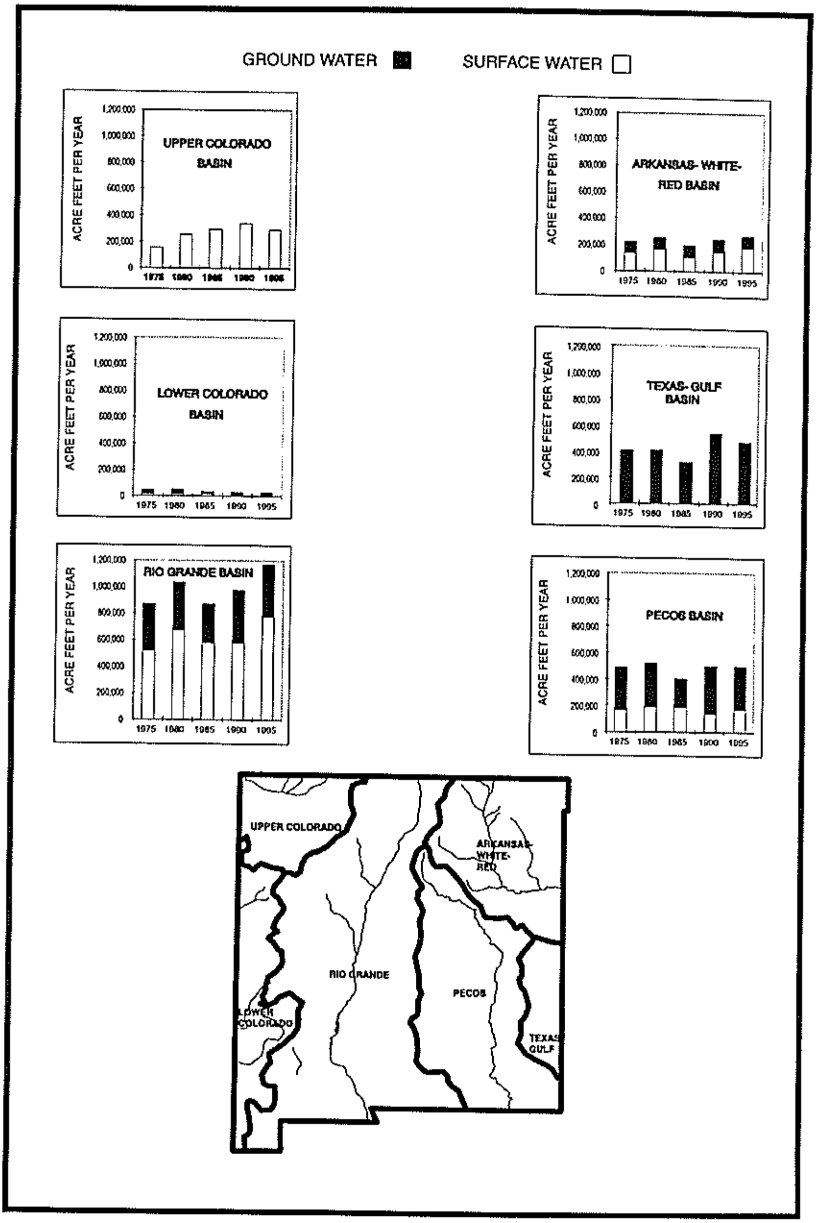


Figure 4. Consumption Use of Ground and Surface Water by Major Hydrologic Basin in New Mexico from 1975 to 1995

and groundwater use for each of these six basins for the 20-year period from 1975 to 1995. The more populated basins generally have higher water use.

WATER RIGHTS

An appropriative water right, like material items, is considered property and can be separated from the land to another location. However, in most states, including New Mexico, the appropriator "owns" only the right to use the water and not the "corpus," or body of water itself. New Mexico law broadly states that "all natural waters belong to the public and are subject to appropriation."

The federal Desert Land Act of 1877, in recognizing the special needs of arid lands, validated the Doctrine of Prior Appropriation. The act provided that water rights on desert land should depend on "bona fide prior appropriation." The Act also provided that all surplus water above actual appropriation and necessary use should be available for public appropriation for irrigation, mining, and manufacturing.

In establishing a water right, two steps must be met. The first is the necessity of constructing a man-made diversion, such as a dam or irrigation ditch. For example, a person who builds a ditch to carry water from the stream to a field is fulfilling the intent of establishing a water right. On the other hand, a person who uses water in a stream for fishing or rafting isn't establishing a right to that water because water hasn't been diverted from the stream. These instream uses are allowed, but are not protected by water rights. At the time of this writing, however, the diversion requirement for establishing a water right for instream flows has been called into question. A March 27, 1998 opinion by the New Mexico Attorney General suggests that a diversion may not be necessarily for establishing instream rights if the right is conditioned on a requirement that accurate flow measuring devices be used in the reach of a stream with the instream flow right.

The second step in establishing a water right is putting water to beneficial use. The New Mexico Constitution states: "Beneficial use shall be the basis, the measure and the limit of the right to the use of water...Priority in time shall give the better right." The constitutions of a majority of the western states contain language similar to New Mexico's in determining water rights.

Although the law sets beneficial use as its standard for granting a water right, and sets penalties for uses that aren't beneficial, the law doesn't specify what those uses are. Generally, nearly all uses are considered beneficial, whether water is used for agriculture, recreation, industry or secondary recovery of oil. New Mexico courts have validated uses such as stock watering as a beneficial use. However, the law does classify the "willful waste of surface or underground water to the detriment of another or the public" as a misdemeanor. "Willful waste," then, is not a beneficial use. In New Mexico, all beneficial uses are considered equal regardless of the economic value produced by the use.

WATER RIGHTS ADMINISTRATION

New Mexico historically has considered its water a public resource, and early on set forth rules governing its use. The 1907 Water Code states that "all natural waters flowing in streams and watercourses, whether such be perennial or torrential, within the limits of the state of New Mexico, belong to the public and are subject to appropriation for beneficial use."

The 1907 Water Code referred only to the state's surface water because at that time the technology for groundwater development was in its infancy. The state's original water rights laws, then, applied only to surface water. At the turn of the century, however, farmers first began using the Roswell Artesian Aquifer for irrigation and by 1909 over 800 wells were drilled. By 1916, the pumping had depleted the aquifer to the extent that the area in which artesian (flowing) wells could be found had significantly diminished. In 1927, the legislature passed a bill which addressed groundwater and it generally paralleled the state's surface water code. In 1931 the groundwater code was slightly revised and reenacted substantially in its present form. Sixteen western states followed New Mexico's lead to some degree when establishing their groundwater regulations (Harris, 1984).

The state engineer's initial jurisdiction over the state's surface water now includes responsibility over groundwater in declared groundwater basins. When the state engineer finds that the water of an underground source has reasonably ascertainable boundaries, he can assume jurisdiction over the appropriation and use of such water by "declaring" or describing the administrative boundaries of the basin. Within a declared underground water basin, no well may be drilled without a permit and drilling may be done only by a well driller licensed by the State Engineer Office. Currently declared groundwater basins cover an area encompassing about 90 percent of the fresh groundwater in the state.

The state engineer makes a declaration to protect prior appropriators, to guarantee the water's beneficial use and to ensure the orderly development of the resource. He may declare a basin without prior notice. However, after declaring the basin, he must hold a public hearing on the declaration within a specified time. The state engineer has no jurisdiction outside declared underground basins, except to prevent waste.

Declaring a basin has no effect on water rights initiated before the declaration date. After that date, however, those wanting new water rights or wanting to drill replacement wells for an existing right must apply to the state engineer for a permit. If it is determined that all groundwater in a basin has been fully appropriated, no new water rights will be issued. Although this situation is commonly referred to as being a "closed basin," the correct term is "fully appropriated."

ADJUDICATION OF WATER RIGHTS

Although the State Engineer Office plays an administrative role, rather than a legal one, New Mexico statutes grant the authority of that office in the adjudication of water rights disputes. An adjudication is the legal action taken either by individual appropriators or by the state engineer to protect a water right and to ensure that it is properly recognized by the courts. A water right adjudication is similar to a title search used to investigate and guarantee proof of the ownership of property such as a house or land.

Adjudications, especially in water rights disputes, often depend on scientific studies for validation. The court can require the state engineer to provide this scientific information. For example, the court normally requires him to furnish a complete hydrographic survey of a stream system or groundwater basin under dispute to determine the rights involved. The hydrographic survey typically includes a detailed survey and inventory within a defined basin of who is beneficially using water, where the water is being diverted or pumped, how much is being used, where it is used and the priority dates of its use.

The court has the jurisdiction to hear and determine questions necessary for the adjudication of all water rights within a stream system. During adjudication, the court, armed with scientific studies and other factual information, makes the final determination on the amount of water allocated to the right and its priority date.

LIMITATIONS AND CONSTRAINTS ON WATER RIGHTS

New Mexico, through interstate compacts, gets an equitable share of the surface water flowing through the state. In turn, however, it can't use so much water that a downstream state fails to receive its equitable share. The Bill of Rights in the U.S. Constitution protects a water right, which is legally considered property, by virtue of its prohibition against taking private property without due process of law and just compensation.

New Mexico's 1907 Water Code set the criteria for rights to the state's water. The code also confirmed the priority of water rights established before that date. Those pre-1907 water rights, based on historical use, are called vested rights and date from the initiation of the claim. Since 1907, anyone wanting a surface water right has had to apply for a permit to the territorial or state engineer.

Individuals with senior water rights have priority over those with junior water rights. The seniority, however, applies only to the water in the original right. Any surplus water becomes available to junior appropriators. In dry years, not uncommon in the Southwest, the more junior the right, the less likely it is that the junior right holder will get water.

Interstate Compacts

One constraint in apportioning surface water is that most of New Mexico's surface water supplies also are governed by eight interstate compacts to which New Mexico is a party. Although the Constitution forbids alliances and treaties between states, it does permit states to enter into agreements, or compacts, with the consent of the U.S. Congress. Compacts generally supersede state law and are preferable to judicial procedures in resolving interstate water conflicts. Compacts generally have the flexibility to meet changing physical and economic conditions.

States that share a common surface water resource enter into a compact first by reaching an agreement among the states concerning the conditions of the compact. Then, when the legislature of each state involved ratifies the compact, it is sent to each state governor for approval. After state approval, the compact is sent to the U.S. Congress for approval and then to the President where it is signed into law.

The Rio Grande Compact, which was adopted in 1938, is the major compact affecting New Mexico. The compact divides the river water, indexed to flows at various gaging stations, among Colorado, New Mexico and Texas. Its purpose is to ensure that each state continues to receive its share of the surface water supply. The Pecos River, Colorado River, Upper Colorado Basin, La Plata River, Canadian River and Costillo Creek compacts also have had considerable importance in determining New Mexico's relations with its neighboring states. The table below summarizes New Mexico's compacts. In addition to these compacts, New Mexico must also abide the terms of an international treaty between the United States and Mexico. This treaty, the 1906 Rio Grande Convention Treaty, was to provide for the equitable distribution between the United States and Mexico of the Rio Grande waters for irrigation purposes (34 Stat. 2953). The treaty required

NEW MEXICO'S INTERSTATE WATER COMPACTS

Compact	Parties to Compact	Date Signed
Colorado River Compact	Arizona, California, Nevada, Colorado, New Mexico, Utah and Wyoming	November 22, 1922
La Plata River Compact	Colorado and New Mexico	November 27, 1922
Rio Grande Compact	Colorado, New Mexico and Texas	March 19, 1938
Upper Colorado River Basin Compact	Arizona, Colorado, Utah, New Mexico and Wyoming	October 11, 1948
Costilla Creek Compact	Colorado and New Mexico	September 30, 1944
Pecos River Compact	New Mexico and Texas	December 3, 1948
Canadian River Compact	Oklahoma, New Mexico and Texas	December 6, 1950
Animas-La Plata Project Compact	Colorado and New Mexico	June 30, 1968

that the United States deliver to Mexico 60,000 acre-feet of water annually. The delivery is to be in the Rio Grande bed, at the point where the headworks of the Acequia Madre then existed, above the city of Juárez, Mexico.

Interstate Groundwater Transfer

Under a January 1983 Federal District Court decision, New Mexico can no longer prohibit the out-of-state export of groundwater. New Mexico's statute banning the export of its groundwater was struck down as violating U.S. Constitutional protections for interstate commerce. The decision was based, in part, on the decision of the U.S. Supreme Court in *Sporhase v. Nebraska* in which the court ruled that water was an article of commerce and that states are therefore limited in their power to ban its export. The Sporhase decision has made state water laws more vulnerable to constitutional challenge. In Sporhase, the court held that the state's interest in conserving and preserving scarce water resources in the arid West clearly has an interstate dimension. The state could not, however, totally prohibit the export of state waters.

Because of the 1983 Federal District Court decision, New Mexico's 1983 Legislature passed a law which presently allows groundwater export under certain conditions. The law states that: In order to approve an application under this act, the state engineer must find that the applicant's withdrawal and transportation of water for use outside the state would not impair existing water rights, is not contrary to the conservation of water within the state and is not otherwise detrimental to the public welfare of the citizens of New Mexico.

Under the new law, the state engineer considers several factors in deciding whether to approve a permit to withdraw water from surface or groundwater sources in New Mexico for transport outside the state. The law then lists six of the factors to be considered:

- the supply of water available to the state of New Mexico;
- water demands of the state of New Mexico;
- whether there are water shortages within the state of New Mexico;
- whether the water that is the subject of the application could be transported feasibly to alleviate the water shortages in the state of New Mexico;
- the supply and sources of water available to the application in the state where the applicant intends to use the water; and
- the demands placed on the applicant's supply in the state where the applicant intends to use the water.

Water Transfers

The days of new water appropriations are coming to an end and new demands will be accommodated by transfers of water from existing uses to new uses. In areas of full appropriation (which includes most of New Mexico) water rights become the object of supply and demand. Even in the marketplace, however, water rights are subject to state laws. In New Mexico, a water right is a property right and inherent in that ownership is the prerogative to change the point of diversion, place or purpose of use of the right. These changes, however, are governed by the overriding question of whether or not the change will impair existing water rights holders (Brown et al., 1992). Simply, if the change would result in an impairment to other rights, the transfer won't be allowed. The right retains its priority date and its quantity of water as long as the right continues to be exercised.

Although the right to water may be transferred with the sale of the land, unless reserved in the deed, a water right can be sold separately from the land and sold for a new use in another area (an application to the state engineer is required). For example, an owner can sell the rights in one area for use in another area if the transaction will not impair other rights in the new area. By doing so, he withdraws the use of that water in the first area. The water withdrawn from use is adjusted for losses associated with the change of the point of diversion and credited to the water supply in the second area. The new owner then is allowed to draw from the credited supply.

Most water rights transfers today are groundwater transfers from agricultural uses to municipal, commercial or industrial uses. It is again important to stress that under New Mexico law, all beneficial uses are equal regardless of the value of the use.

A water right transfer does not always mean a new owner. A transfer can mean that the owner wants to change the use of the water, the amount of the allocation, or the location of the well under his recognized water right. Changes in place and purpose of use or changing the location of a well require application to the state engineer and then showing that the change would not impair existing rights.

In the case of well location changes, the transfer might simply mean that the owner wants to "rearrange" wells or drill replacement wells. For example, a farmer wanting to take a water right from one field and use it on a second field, which he also owns, applies to the state engineer for that change. The change may be allowed depending on the water source location, location of other water rights, and return flow. Another instance might be where an owner applies for a permit to move a well because the casing in an old well was broken and could not be repaired.

The state engineer must guard against injury to downstream users from upstream changes. This is especially true of changes that affect depletion. Depletion is the amount of water actually consumed and not returned to a surface or groundwater system. A water right owner, for example, might want to change his use from agricultural to domestic, which would decrease the depletion percentage of the total amount diverted. In agriculture, for example, as much as 70 percent of the water delivered to a field actually may be consumed. The remaining 30 percent could seep back to the water source as return flow and be available for other uses.

Municipal use is somewhat different. In a subdivision, for example, 50 percent or more of the water delivered could be returned to the water supply as sewage effluent (consider the fact that one of the larger surface water streams in the state of New Mexico is Albuquerque's wastewater effluent!). In contrast, road construction depletes nearly 100 percent of its withdrawal. A use in a new location is never allowed to deplete more water than was granted in the original permit.

A change within an agricultural use can affect the amount of water depleted, but if the use is changed from one type of crop to another, the state engineer doesn't require a new permit. This type of change is allowed because the water use within a given area is determined by the average cropping pattern for the area, not on the amount used on a specific field.

In some instances, a new appropriation may be allowed in a fully appropriated basin. In the Rio Grande Basin, for example, a new appropriation of groundwater can be permitted under the condition that the appropriator acquire and retire, or withdraw from use, water rights in amounts sufficient to compensate for the increasing effects of pumping on the stream. This retirement scheduling ensures that the supply for continuing surface water rights will not be impaired while permitting the new user to take a large portion of his supply from groundwater. The appropriator is, in effect, buying up, but not using, surface water in order to obtain rights to groundwater.

COPING WITH SCARCITY

From what has been presented in the preceding overview of New Mexico's water situation it should be clear that as our population increases we will face increasing water scarcity in the future. The conditions of water scarcity that gave rise to our prior appropriation system have been constant over time, but the demand for water has been expanding. Where population once was dispersed widely in the state, it is now highly concentrated in urban areas where municipalities are placing increasing demands on a finite water supply. Most experts agree that in the foreseeable future it is not likely that New Mexico will discover new water sources or in some other way be able to significantly augment our water supply.

The Complexity of Water Conservation

The sight of cropland recently flooded with irrigation water is common in many places in New Mexico. It is also common, particularly among many city dwellers and newcomers to our state, for many to believe that irrigation is a wasteful practice that should be eliminated or at the very least, be made much more efficient. With irrigated agriculture accounting for well over 80 percent of the total water consumed in New Mexico, one could make a simple calculation and conclude that by reducing agricultural water consumption by slightly over 10 percent one could potentially "free up" an amount of water nearly equal to all other uses combined. This is a simple answer to a very complex question. The late Steve Reynolds, former New Mexico State Engineer, once said that for every complex water problem there is a simple answer - and it is usually wrong.

The notion that water conservation can bring about water savings and "free up" water for additional beneficial use is not always the case. Since the only true losses of water to the system through agricultural activities are by evaporation and plant transpiration, true "savings" can only occur when these types of losses are reduced. This raises some complex questions. For example, is water really saved when a farmer concrete lines an irrigation ditch? This may reduce seepage loss into the ground but that so called "loss" may represent groundwater recharge that another user may be dependent upon. Concrete lining of canals can also speed the movement of water downstream, but in some cases this simply means that more water might end up in a reservoir and be subject to evaporation loss!

Is water really saved by shifting to irrigation practices that may reduce the actual amount of water applied to the farm field? If doing so leaves more water behind in a shallow river system, where greater evaporation may take place, more water might actually be lost from the system. It is important to recognize the complexity of these issues and the many misconceptions about alleged "waste" in agriculture.

Good Agricultural Practices

Agricultural irrigation practices are addressed under water right statutes separate from those dealing with water conservation. Early on, the New Mexico legislature recognized that trying to set up formulas describing limits on the amount of water to be allowed in agriculture was not feasible. Early attempts to do this met with continual amendment and finally the adoption of Section 72-5-18 NMSA. This long standing provision in New Mexico water law states that the amount of water allowed for irrigation purposes ***"...shall be based upon beneficial use and in accordance with good agricultural practices and the amount allowed shall not exceed such amount. The state engineer shall permit the amount allowed to be diverted at a rate consistent with good agricultural practices and which will result in the most effective use of available water in order to prevent waste."***

Under this statute it has been recognized that the duty of water (the amount necessary for the successful cultivation of land) includes five essential factors: (1) the amount of water diverted; (2) the place of diversion as related to use; (3) the amount of water necessary for a particular crop or land; (4) season of the year; and (5) the general irrigation or water-using practices followed in the area.

Thus, permitted water rights for irrigation, as practiced throughout New Mexico today, have generally been recognized as having already met the test of being "consistent with good agricultural practices" and under New Mexico law are probably not wasteful practices. This, however, is not to say that by utilizing new irrigation technologies that these practices could be significantly improved and more water could be "freed up" and made available for other uses.

Water Conservation Incentives

Since New Mexicans first began to irrigate, science and technology have made the process more efficient and increasingly sophisticated. Irrigation methods continue to improve such that more of the applied water is used in crop growth and less is lost to such factors as evaporation and non-recoverable deep percolation. The adoption of more water efficient practices by farmers depends on a host of factors, the more important of which relate to economics.

It is important to recognize that any given water management practice which may work well under one set of conditions may not be generally applicable to all terrain, soil types, geographical locations or cultural settings of an area. Each practice has to be tailored to the unique features of the region and, in many cases, even to different areas within individual farms. The rich diversity of irrigation practices seen across New Mexico is the result of decades of trial and error to discover which techniques work best.

Improving on-farm efficiency of water use (increasing crop production or profits for a given quantity of applied water) is a process driven by incentives. There are always risks and usually increased capital outlays associated with changing to new and hopefully more efficient irrigation systems. A farmer weighs these risks against potential benefits and a decision is made. If one of the benefits is a savings of water while at the same time maintaining the same level of crop production, the irrigator is faced with the question of will the "saved water" be his to use, lease or sell or will it be taken from him because it was not put to beneficial use. If it is the latter, there is obviously no incentive to become more efficient in his irrigation practices.

With the bulk of New Mexico's water rights held by the agricultural sector and with municipal and industrial water demands growing at such a rapid rate, there are powerful political and market forces at work to move agricultural water to the urban sector of the economy. If there was a clear policy allowing an irrigator to market "saved water," there would be strong incentives to the farmer to become more efficient in his irrigation practices. Currently, New Mexico has no such policy. The following is a more detailed illustration of this issue.

Real Water Savings on the Farm

The state engineer in administering agricultural water rights uses a term called Consumptive Irrigation Requirement (CIR). The CIR is the amount of applied water transpired by and incorporated into the plant tissue of the crop. It also includes the amount which evaporates from the soil surface near the plants. The CIR is the consumptive water use of a crop which is lost from the system and no longer available for other users. The state engineer considers the CIR as the **only** portion of a water right which may be sold or leased as a property right. It is calculated based on average crop needs in a region. Figures 5 and 6 are graphic representations of the movement of water through a typical surface irrigation system and illustrate the CIR component along with other losses in the system.

The amount of water an irrigator diverts from a farm headgate or a groundwater well is always greater than the CIR because there are other losses as the diverted water makes its way to the roots of the crop. These losses can include deep percolation past the root zone in a field, leakage from unlined ditches or runoff. These are shown as black arrows in the figures. Generally, these are not really true losses from the system because this water eventually becomes available to

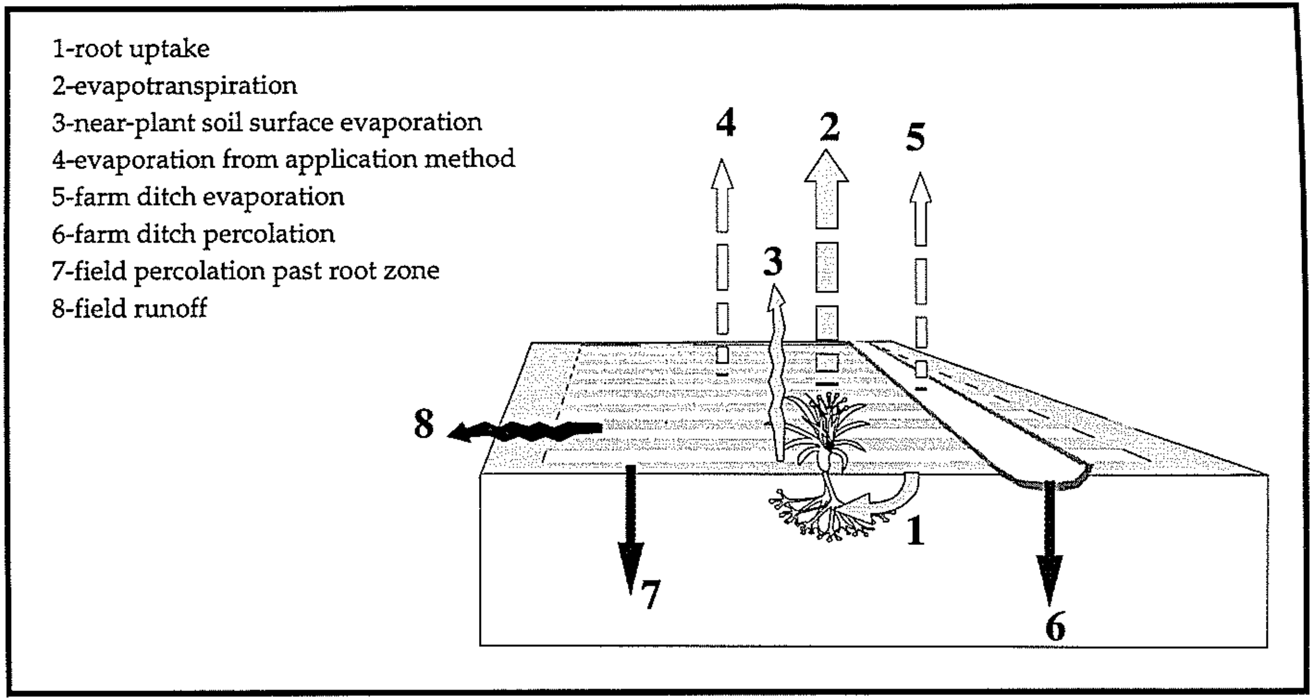


Figure 5. On-farm depletions, losses and return flows. White arrows are incidental depletions (evaporation), black arrows are return flows and gray arrows are the Consumptive Irrigation Requirement (CIR).

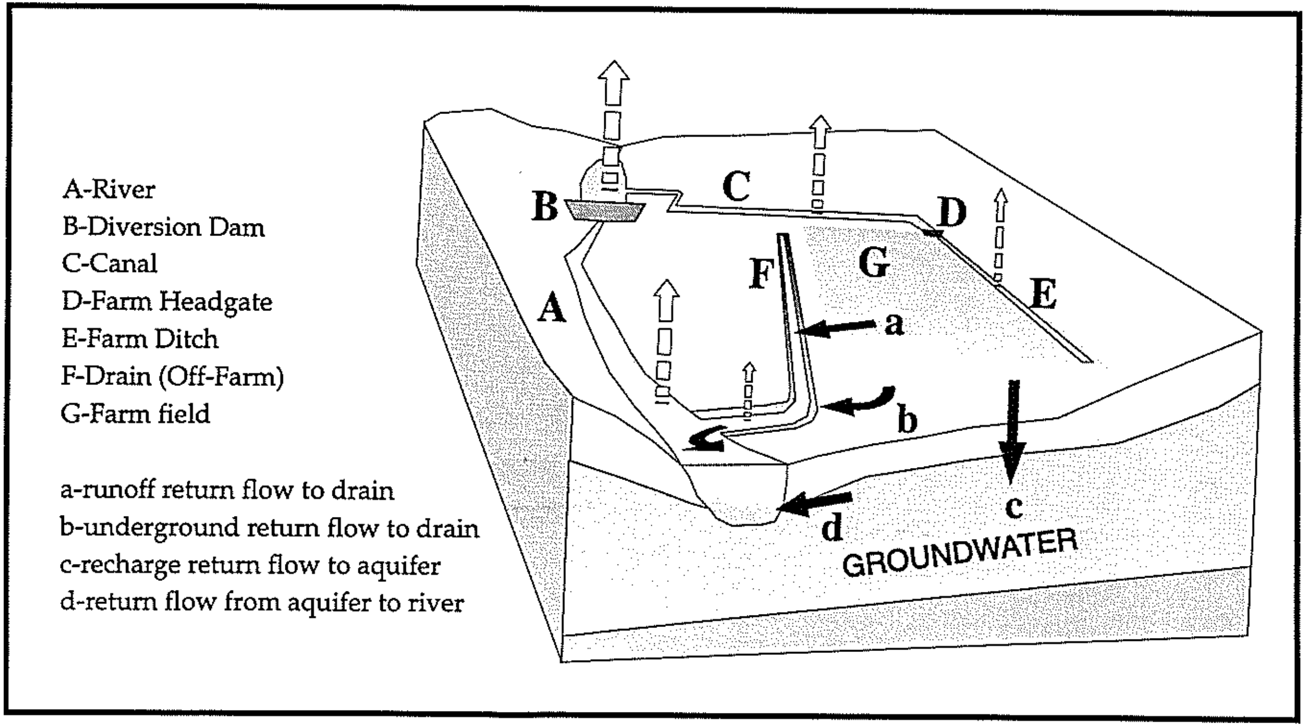


Figure 6. Off-farm depletions, losses and return flows. White arrows are incidental depletions (evaporation) and black arrows are return flows.

other users as recharged groundwater or drain return flows to a river. An exception to this, however, might be a situation where deep percolation of fresh water mixes with an underlying saline water aquifer rendering it unusable for subsequent use. Reducing return flows by changing irrigation practices does not really represent savings in terms of reducing permanent losses from the hydrologic system. The state engineer does not consider these return flows as a water right which can be sold or leased as a property right. This water is considered to be owned by the public. The irrigator only temporarily "borrows" it with the understanding that it must be returned to the system.

There is another category of losses which the state engineer calls **Incidental Depletions**. This is water which evaporates from ditches and fields from surface irrigation or water which evaporates from sprinkler irrigation. These losses are shown for both on-farm and off-farm components of an irrigation system as the white arrows in Figures 5 and 6. Unlike the runoff and deep percolation losses mentioned above, these losses **do not** become available to other water users as return flows. They are true losses from the system and these losses can be significant. A sprinkler system, for example, can annually lose over one half an acre-foot per acre through evaporation. Flood irrigation might only evaporate a tenth of an acre-foot per acre per year and a buried drip system virtually none.

Utilizing irrigation technology which reduces evaporation (incidental depletions) would appear to offer opportunities for real water savings. Switching from sprinkler irrigation to a buried drip system on a 100 acre field, for example, could save 50 acre-feet per year (about 16 million gallons). That savings, if it could be transferred, could serve the needs of roughly 225 city dwellers. The central question is, does the farmer who creates the savings have the right to continue to irrigate his crops with his new and highly efficient drip system and sell or lease his saved water? The current interpretation of policy is **NO**, he can not because the saved water had also belonged to the public and the evaporation is just a necessary cost of doing business. This may make sense in the case of return flows where "losses" are returned to the system for other users but it is difficult to understand how water vapor (incidental losses) can be of much use to a downstream user.

Changing to an efficient drip irrigation system involves not only a large capital investment but the new system requires new management skills and constant attention and maintenance. Common sense would suggest that an irrigator would need more of an incentive to change to such a system than just that warm feeling he might get in knowing that conservation is, of itself, a noble thing to do. In reality, the irrigator looks at his choices from an economic point of view. If he could sell or lease this saved water and continue to raise his same crops he would certainly realize economic benefits and at the same time foster the purposes of conservation. Such a situation is certainly consistent with the doctrine of maximum utilization which is deeply rooted in New Mexico water law. Some have suggested that if the policy were changed to recognize saved incidental depletions as a transferrable water right to be owned by the person who brings about the savings, such a policy change would encourage waste. One line of reasoning is that an irrigator might, for example, shift from a reasonably efficient flood irrigation system to a less efficient sprinkler system to establish higher incidental depletions as part of his water right. The irrigator might then, at a later date, switch back to flood irrigation and claim ownership of a greater amount of saved incidental depletions. It would seem that this type of situation could be avoided through prudent administration of the existing water laws.

With the relative scarcity of New Mexico's surface and groundwater resources, comes the inevitable political and philosophical debate as to the best method for allocating these resources among constituents of a democratic society. The marketplace and common sense would appear to be good starting points for allocating property rights in water.

Information Needs

Rarely do problems capable of technical solutions escape examination by the scientific community when there is a pressing social need to solve them. For reasons probably related to economics, in the arid West and particularly in New Mexico, the issue of quantifying water resources **on a site-specific basis** has somehow fallen outside the scope of traditional research. The data collection required to obtain the necessary level of detail can be very expensive. While much basic and applied research in the hydrological sciences has originated in New Mexico, actual field-level data gathering has been rapidly outpaced by development of increasingly sophisticated computer models. Any model however, no matter how well designed and mathematically refined, is only as good as the data put into it.

In addition to hydrologic data about aquifers, an equally significant need is for more and better information about the amount of surface water available on a reliable basis. First, how much can be reliably expected to flow down our rivers and streams and second, how does that quantity infiltrate into the aquifer? In the Rio Grande, for example, there are insufficient stream gauges to answer these questions. The amount of seepage through the stream channel at critical points where the greatest amount of groundwater pumping has and will take place is a vital question which needs to be determined in many areas. Only very rough estimates are currently being utilized to answer these significant questions.

In New Mexico there is also a lack of ecological information on most of the state's waterways and no single agency is charged with collecting it. This includes a related lack of information on riparian conditions along these waters. This type of biological information is becoming increasingly important as water resources managers must consider the environmental impacts of actions which may change water flow regimes.

We are all aware of water disputes which have frequented New Mexico's history. Many of these disputes have been fueled by ignorance and have diverted valuable public and private resources into legal proceedings, redesign of projects, expensive acquisition of water rights and other unnecessary expenditures. Those disputes could have been avoided by better knowledge of the resource. There is little question that water is vital to our economic development and its prudent management is necessary to assure a high quality and sustainable water supply for the future.

Governmental policy decisions are often motivated by crisis or the perception of crisis. In the case of water resources management, a perceived crisis can bring about water conservation reform. Of course, conservation can be valuable whether or not scarcity is imminent. Deterring economic development before all facts are in, however, can be equally dangerous. Perceived shortages, if not real, can also lead to unwarranted reallocation of water rights, for example, from agriculture to municipal and industrial use.

Lack of information about the sustainability of water resources in New Mexico has created confusion and uncertainty among the general public. This can lead to unwarranted constraint of economic development in those areas of the state having water resources capable of supporting new development as well as over-development in other areas which may have serious water limitations.

Because much of New Mexico is located on semiarid land, it is self-evident that water supplies are finite. This does not mean, however, that snow melt from the mountains is going to cease, that large quantities of groundwater in storage are disappearing or that there is insufficient water for future growth. Rather, this means that as New Mexico communities continue to grow, they must undertake to more carefully manage water demand through such measures as conservation and water reuse. Equally important is to develop a better understanding of the quantity, quality and dependability of surface water supplies and the relationships of surface supplies to groundwater. Most importantly, we must bridge the gap between our scientists and policy makers in order to develop effective policies.

SUMMARY

New Mexico is rapidly approaching the time when any new water uses will have to be accommodated by water transfers from existing uses. With well over 80 percent of current water use being consumed by the agricultural sector, there are increasing pressures for water transfers to occur from irrigated agriculture to municipal and industrial uses. New Mexico has enacted and administered a comprehensive body of water law which has served the state well for many years. There appear to be opportunities, through agricultural water conservation, to accommodate increasing municipal and industrial demands, but changes in policy are needed as incentives to do so. Developing more in-depth scientific information about the nature and extent of our water resources will continue to be a vitally important ingredient for the wise management of this important resource.

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GROUNDWATER RECHARGE: THE LEGAL REALITIES OF KEEPING THE HYDROLOGIC SYSTEM WHOLE

Tessa T. Davidson[3]

> . . . water was placed in a unique category in our Constitution – something that cannot be said of lumbering, coal mining, or any other element or industry. The reason for this is of course too apparent to require elaboration. Our entire state has only enough water to supply its most urgent needs. Water conservation and preservation is of utmost importance. Its utilization for maximum benefits is a requirement second to none, not only for progress, but for survival.[4]

INTRODUCTION

At its inception in the late 1800s, New Mexico water law focused on protecting agrarian uses of surface water. Although the law has evolved to allow diversions of groundwater for irrigation and other purposes, it has done so within the framework of protecting surface water uses. Protecting New Mexico's surface water supplies, and individuals' rights to those supplies, has created the legal legacy to "keep the river whole."[5]

Today, competition is increasing for all sources of water in New Mexico. In order to sustain urban growth, and protect the riverine environment, the focus has started shifting from keeping the river whole, to protecting the viability of the entire hydrologic system.

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[3] Attorney with Swaim & Schrandt, P.C., Albuquerque, New Mexico.

[4] Kaiser Steel Corp. v. W.S. Ranch Co., 81 N.M. 414, 417, 467 P.2d 986, 989 (1970).

[5] Statement made by New Mexico State Engineer Steve Reynolds in his memorandum decision on the City of Albuquerque's applications Nos. RG-960 through RG-963, November 4, 1957.

Aquifer injection projects and investigations into uses for non-potable surface water are becoming necessary realities for water planners and administrators within the state. As a result, New Mexico law makers have begun to feel the clash between traditional surface-water doctrines and the new conservation paradigms designed to protect all water supply sources.[6]

Because water stored underground is free from evaporative loss, groundwater replenishment is one conservation tool by which future water supplies may be secured. However, New Mexico water law does not currently recognize, nor does it provide for, groundwater replenishment or "recharge" activities.[7] The United States Bureau of Reclamation's two-prong definition of "groundwater recharge" may provide New Mexico some guidance in recognizing recharge activities in the state: 1) a controlled activity that enhances the natural replenishment of an underground aquifer; and 2) the sponsor of the activity intends to store the water or use it immediately for a beneficial purpose as defined by state law.[8] For the purposes of this article, recharge that is accomplished through active efforts is distinguished from recharge that occurs passively, or as an incidental by-product of surface water uses. "Active" recharge includes groundwater replenishment through spreading basins, recharge pits, injection wells, infiltration galleries, and other direct means of

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[6] Despite strong efforts, New Mexico has not yet adopted comprehensive water conservation legislation nor legislative incentives for preservation of water supplies. During the 1998 New Mexico Legislative Session, a water conservation bill was proposed and supported by the New Mexico Office of the State Engineer. The session also considered statewide water banking legislation. However, both bills were tabled in committee in part because it was argued they failed to protect expectations regarding private water rights under New Mexico water law.

[7] Statutes governing oil and gas recovery activities in New Mexico provide for a type of groundwater replenishment by injecting low quality water into the shallow aquifer. This water is not intended for future beneficial use per se, and the "recharge" activity itself does not create a water right under state law.

[8] Western States Water Council, Groundwater Recharge Projects in the Western United States: economic efficiency, financial feasibility, and legal/institutional issues, I-3, (October, 1990).

enhancing existing groundwater supplies.[9] "Incidental" recharge refers to replenishment that is accomplished by water seepage, leaking, and percolation from surface-water delivery and drainage systems, and storage facilities.[10]

To encourage the conservation and enhancement of existing groundwater in storage, New Mexico lawmakers must endeavor to fine-tune New Mexico's water code to provide for the recognition and protection of water rights used for groundwater recharge. This article analyzes the current legal constraints on implementing recharge projects in the state by: 1) providing a brief discussion of New Mexico water law; 2) illustrating how current state law discourages using water rights for recharge activities; and 3) suggesting possible changes in state law and policy to provide incentives for using existing water rights for recharge purposes.

SUMMARY OF NEW MEXICO WATER LAW

New Mexico follows the prior appropriation doctrine of water law as mandated by the state constitution.[11] Under this doctrine, the first user to put water to beneficial use is protected from subsequent appropriators of water. Upon perfecting a water right through beneficial use, a chronological hierarchy is created whereby earlier users receive priority of use over subsequent users. The constitutional protection afforded to prior users of water under the prior appropriation doctrine controls most aspects of water law in New Mexico including the acquisition, administration and perfection of water rights.

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[9] Id.

[10] Although New Mexico has just recently begun investigating the technical viability of active groundwater recharge projects, incidental recharge has been a significant source of groundwater replenishment for many decades. For example, a 1994 study by the U.S. Bureau of Reclamation concluded that the irrigation works of the Middle Rio Grande Conservancy District contributes up to 30,000 acre-feet per year of recharge to the groundwater aquifer that is relied on by the City of Albuquerque for its municipal water supply.

[11] See, N.M. Const., Art. XVI, §§ 2 and 3 that provide "[p]riority of appropriation shall give the better right . . . " and . . . "[b]eneficial use shall be the basis, the measure and the limit of the right to the use of water."

New Mexico's water code provides that all "natural" waters flowing in streams and water courses belong to the public and are subject to appropriation for beneficial use.[12] After 1907, with respect to surface water, and after 1931 in declared underground water basins, the acquisition of water rights by appropriation for beneficial use requires a permit from the New Mexico State Engineer. The State Engineer will not issue a permit to appropriate water if the new appropriation will interfere with existing groundwater or surface water rights, or the new appropriation is contrary to conservation or detrimental to the public welfare of the state.[13]

Waters which seep or otherwise escape from constructed works and "which depend for their continuance upon the acts of man" are not public waters subject to appropriation.[14] Such "artificial waters"[15] are private and subject to beneficial use by the owner provided that the owner exercises dominion and control over the waters. If artificial water actually reaches a water course or an underground reservoir, it is "presumed" the owner has lost control of the water and cannot recapture it.[16]

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[12] N.M. Stat. Ann. 1978 § 72-1-1.

[13] N.M. Stat. Ann. 1978 § 72-12-3.

[14] See, N.M. Stat. Ann. 1978 § 75-2-27.

[15] N.M. Stat. Ann. 1978 § 75-2-27 defines artificial waters as "... waters whose appearance or accumulation is due to escape, seepage, loss, waste, drainage or percolation from constructed works, either directly or indirectly, and which depend for their continuance upon the acts of man."

[16] Reynolds v. City of Roswell, 99 N.M. 84, 654 P.2d 537 (1982). See also, Brantley v. Carlsbad Irrigation District, 99 N.M. 280, 587 P.2d 427 (1985), and Kelley v. Carlsbad Irrigation District, 76 N.M. 466, 415 P.2d 849 (1966).

As enforced administratively by the State Engineer, "passive" water use[17] has not been considered a beneficial use of water.[18] Historically, the State Engineer has required that new appropriations of water be accomplished through a physical, man-made diversion.[19] In the past, the physical diversion requirement served somewhat of a regulatory function by giving notice to would-be appropriators that a water right was established in a particular location. However, New Mexico court's have not examined whether a valid water right can be established by a user who intends to "passively" use water without a physical diversion. The New Mexico Supreme Court has only upheld the State Engineer's requirement of a physical diversion in the context of establishing an agricultural water right.[20]

Once a water right is established, the State Engineer is statutorily empowered to ensure that an application to change its point of diversion, place or purpose of use does not result in impairment of others' rights, nor be contrary to conservation nor detrimental to

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[17] Instream flows, storage, and other "in situ" uses of water are examples of passive water use.

[18] However, in a January 8, 1998, Memorandum to State Engineer Tom Turney from the State Engineer Legal Services Division, it was concluded that the State Engineer was not barred by the state constitution, statutes, or case law from granting an application to change the use of an existing water right to instream flows. This Memorandum was relied on, in part, by the New Mexico Attorney General in its March 27, 1998 decision that concluded no constitutional bar exists to prevent the recognition that instream flows constitute "beneficial use" in New Mexico.

[19] State Engineer regulation II-G for Surface Waters provides, "... after completing the works, permittee shall divert water and apply it to his intended use." The State Engineer has relied on the references to constructed water "works" throughout New Mexico's water code for its requirement that there be a physical diversion for beneficial use.

[20] See, State ex. rel. Reynolds v. Miranda, 83 N.M. 443, 439 P.2d 409 (1972). In Miranda, a rancher was harvesting and grazing stock on grass produced by a natural wash. The court held that the lack of a physical diversion was sufficient evidence to indicate that the rancher did not intend to appropriate water. Thus, the Court's holding turned on the rancher's lack of intention to appropriate as evidenced by the absence of a physical diversion.

public welfare.[21] The State Engineer must make impairment[22] determinations because he is bound by New Mexico's water code to protect existing water rights. In cases where ground and surface water are hydrologically connected, the State Engineer may place conditions on a permit to pump groundwater to protect existing surface-right holders.[23] For example, the State Engineer may predict the annual stream flow depletion that will result from a groundwater appropriation and require the appropriator to acquire and "dedicate" [24] existing surface water rights to the surface supply to offset the effects of pumping. If appropriate, the State Engineer may also require the water user to submit a return-flow plan in which the user estimates the amount of water that will return to the hydrologic system after a water right is put to beneficial use. The New Mexico Supreme Court has held that the State Engineer's "conjunctive" management policies

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[21] N.M. Stat. Ann. 1978 §§ 72-12-3, and 72-5-6 and Clodfelter v. Reynolds, 68 N.M. 61, 66, 358 P.2d 626, 631 (1961)(the owner of a water right has the right to change the place of diversion, storage or use of the water if the rights of other users will not be injured thereby)

[22] For the purposes of the State Engineer's authority, impairment is a question of interfering with another user's right to a "quantity" of water, not "quality," and it is a question to be determined on a case-by-case basis. See, e.g., City of Roswell v. Berry, 80 N.M. 110, 452 P.2d 179 (1969)(findings of impairment depend on the facts of each case).

[23] City of Albuquerque v. Reynolds, 71 N.M. 428, 379, P.2d 73 (1962). In the State Engineer Memorandum Decision entered on the City of Albuquerque's applications Nos. RG-960 through RG-963, November 4, 1957, the State Engineer stated, "under proper application, the appropriator may take advantage of groundwater that can be removed from storage without impairment of existing rights, and can take advantage of an accounting of the return flow from his appropriation. The permits applied for could be granted without the danger of any impairment of existing surface water rights under the following conditions: 1) that the amount of water pumped be measured 2) that the amount of return flow be measured 3) that existing rights to the consumptive use of surface water would be retired to the extent necessary to offset the effects of the appropriation on the Rio Grande."

[24] A 1994 Opinion of the New Mexico Attorney General concluded that "the State Engineer's water rights dedication practice and procedure are unlawful as practiced in the past because they preclude full consideration of public welfare, water conservation and impairment to existing water rights at the time the new conditional water right is approved. In addition, there is no express or implied authority for the practice and procedure. Finally, the practice and procedure violate procedural due process requirements." N.M. Atty. Gen. Op. No. 94-07, issued November 23, 1994; revised December 23, 1994. After this opinion was released, the State Engineer issued a moratorium on the dedication policy and required groundwater applicants to submit applications to transfer surface water rights needed for offset purposes.

are reasonable administrative requirements to avoid impairment and to keep groundwater and surface water depletions in equilibrium.[25]

The State Engineer also considers the questions of conservation and public welfare in reviewing water rights applications. Statutes that give this duty to the State Engineer do not define these terms nor do they provide any criteria for their application. Likewise, the State Engineer's office has no regulations to guide the potential applicant in meeting the burden of proving the criteria. Case law suggests that public welfare may be supported by providing evidence of cultural values, environmental benefits, and the like.[26] In general, conservation criterion may be satisfied by showing evidence that a water right will be exercised to prevent waste and that some degree of conservation measures will be implemented.[27]

Perfection of a Water Right Through Beneficial Use

Once water is beneficially used, the right to use the water is perfected and becomes a constitutionally protected property right.[28] Under the New Mexico Constitution, the basis, measure and limit of a water right is "beneficial use."[29] New Mexico does not define nor prioritize specific types of uses, and case law provides little guidance on what is considered beneficial use. For example, a contemporary New Mexico case defined beneficial use as a use "for some purpose that is socially accepted as beneficial."[30]

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[25] In City of Albuquerque v. Reynolds, the Court held that the State Engineer's duty to protect existing water rights includes the duty to conjunctively manage rights to surface and underground waters which are hydrologically connected. 71 N.M. 428, 379 P.2d 73 (1962).

[26] See, e.g., Sleeper v. Ensenada Land and Water Ass'n, Rio Arriba County Cause No. RA-84-53(c) ("the relationship between the people and their land and water is central to the maintenance of . . . culture and tradition") rev'd on other grounds, ____ N.M. _____ (Ct. App. 1988).

[27] An attempt to statutorily require the State Engineer to issue conservation guidelines failed in New Mexico's 1998 legislative session.

[28] New Mexico Products Co. v. New Mexico Power Co., 42 N.M. 311, 77 P.2d 634 (1937).

[29] N.M. Const., Article XVI, § 3.

[30] State ex rel. Martinez v. McDermett, 1995 WL 49741 (N.M. App.).See, also State ex rel. Erickson v. McClean, 62 N.M. 264, 308 P.2d 983 (1957) (if water use is for a useful purpose, then it is beneficial use).

A water right perfected by beneficial use may be exercised in perpetuity, unless it is forfeited for non-use. Forfeiture is a punitive measure taken by the state that deprives an owner of his water right if the right is not used for a period of four years and the non-use persists for one year after notice from the State Engineer.[31] The New Mexico Supreme Court has stressed the public policy value of beneficially using water to avoid a determination of forfeiture:

> *"By forfeiture of the rights which are claimed by . . . [those] who failed to use them, the policy of our Constitution and statutes is fostered, and the waters made to do the greatest good to the greatest number. This is on the theory that the continuance of the title to a water right is based upon continuous beneficial use . . . our water laws [are] intended to encourage use and discourage nonuse or waste . . ."*[32]

Thus, New Mexico water law encourages water users to use their water rights and penalizes them if they discontinue their use. Clearly, the legal reality of forfeiture presents a basic dichotomy between water conservation and the protection of a water right in New Mexico.

The constitutional mandates of prior appropriation and beneficial use underline the doctrine of "maximum utilization" found throughout New Mexico water law.[33] Because water is such a scarce resource in the state, water speculation is legally discouraged. Thus, water not beneficially used reverts back to the public supply and is subject to

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[31] See, N.M. Stat. Ann. 1978 §§ 72-5-28, and 72-12-8 (Cum. Supp. 1995). Exclusive from forfeiture is the issue of abandonment. As in general property law, abandonment is the relinquishment of the property right by the owner with the intention to forsake or desert it. Forfeiture does not require the element of intent.

[32] State ex. rel Reynolds v. South Springs, 80 N.M. 144, 147-148, 452 P.2d 478, 481-482 (1969)(emphasis added).

[33] See Kaiser Steel v. W.S. Ranch Co., 81 N.M. 414 (1970).

re-appropriation. The legacy of maximum utilization has resulted in the refusal to recognize "in situ" water uses as constitutionally protected uses of water in New Mexico.

THE CHARACTERIZATION & REGULATION OF GROUNDWATER RECHARGE: WASTE OR BENEFICIAL USE?

In some states the replenishment of groundwater aquifers is a beneficial use.[34] In other states, the recharge of groundwater is not considered beneficial, but the ultimate use of the water may be.[35] If, under existing New Mexico law, recharge can be classified as beneficial use, recharge activities would be subject to state regulation as are other uses of water. Although New Mexico courts have not directly addressed the issue, case law suggests that groundwater recharge may not be considered a beneficial use but may even be considered "waste," to the extent that otherwise usable surface waters cannot be recoverable.

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[34] See Cal. Water Code § 1242 (West, 1971) (The storing of water underground, including the diversion of streams and the flowing of water on lands necessary to the accomplishment of such storage, constitutes a beneficial use of water if the water so stored is thereafter applied to the beneficial purpose for which the appropriation for storage was made); See also Idaho Code § 42-4201 (1990) ([t]he appropriation and underground storage of water by the aquifer recharge district hereinafter created for purposes of groundwater recharge shall constitute a beneficial use and hereby authorizes the department of water resources to issue to the aquifer recharge district a permit, pursuant to section 42-203, Idaho Code . . . .); and Or. Rev. Stat. Ann. § 537.135(1) (1988) (The appropriation of water for the purpose of recharging groundwater basins or reservoirs is declared to be for a beneficial purpose.).

[35] See Ariz. Rev. Stat. Ann. § 48-4401 (Supp. Pamp. 1995) (effective January 1, 1996 as amended by Laws 1994, ch. 223, § 113) and § 45-832.01 (Water that has been stored pursuant to a water storage permit may be used or exchanged only in the manner in which it was permissible to use or exchange the water before it was stored, and only in the location in which it was permissible to use before it was stored.); See also Nev. Rev. Stat. Ann. § 534.015 (Michie, 1986) (Defines "recharged water" as water that reaches or percolates into an aquifer or system of aquifers: 1. Through natural processes; 2. By secondary recharge as a result of beneficial uses; or 3. Artificially through facilities specifically constructed for that purpose.); and Nev. Rev. Stat. Ann. § 534.020 that specifies all underground waters within the boundaries of the state belong to the public, and, subject to all existing rights to the use thereof, are subject to appropriation for beneficial use only under the laws of the state relating to the appropriation and use of water and not otherwise.

The New Mexico Water Code prohibits water "waste."[36] In State ex rel. v. McLean, the New Mexico Supreme Court held that a water user lost his appropriative water right because he was wasting water and such waste constituted non-beneficial use.[37] The water user was allowing an artesian well to run uncontrollably over grazing land without attempting to control it. The court held that state law "contemplates the economical use" of water because "water is too valuable to be wasted through extravagant application for the purpose appropriated or by waste by misapplication which can be avoided by the exercise of a reasonable degree of care to prevent loss . . ."[38] Thus, in McLean, the court equated "waste" with the "loss" of water.

The United States Court of Appeals for the Tenth Circuit also examined the concept of waste in Jicarilla Apache Tribe v. United States.[39] The court held that a contract between the City of Albuquerque and the U.S. Bureau of Reclamation was invalid because the City's storage of San Juan-Chama Project water in Elephant Butte Reservoir for recreation purposes was "wasteful." The court determined that the storage reservoir resulted in extreme evaporation losses (93 percent over a forty-year storage period) and, therefore, the contract was invalid under state and federal water law. The court determined that "maximum utilization" was a fundamental requirement for water use to be beneficial under New Mexico law.[40] The Tenth Circuit also recognized that an appropriator must take reasonable care to avoid waste caused

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[36] See, N.M. Stat. Ann. 1978 § 72-8-4 that provides, ". . . the willful waste of surface or underground water to the detriment of another or the public, shall be a misdemeanor."

[37] 62 N.M. 264.

[38] Id., at 271-271 (emphasis added).

[39] 657 F.2d 1126 (10th Cir. 1981).

[40] Id., at 1133 (Citing Kaiser Steel v. W.S. Ranch. Co., 81 N.M. 414, 417, 467 P.2d 986, 982 (1970)).

by extravagant application of water or by misapplication of water for a non-beneficial use.[41]

Because water is deemed legally "wasted" when otherwise usable water is lost to the hydrologic system and cannot be recovered, the factual issue becomes, how do water administrators and the courts ensure that water used for recharge activities is not lost to the hydrologic system? In the case of active recharge projects, the amount of water injected into and recovered from a viable recharge site can be measured and monitored.[42] Because the dangers of waste can be minimized, it is not difficult to envision that water used for active recharge could receive protection under New Mexico law.

It is more difficult to envision incidental recharge as deserving protection under state law because such recharge is difficult to measure. In <u>State ex. rel. Reynolds vs. King</u> the New Mexico Supreme Court indirectly addressed the issue of recognizing incidental recharge as beneficial use.[43] In <u>King</u>, a trial court refused to uphold the right of a landowner to recover water recharged into an underground basin below a private lake located on his land. When the landowner claimed the right to use the "recharge" water without applying for permit from the State Engineer, he was enjoined for failure to make an application to appropriate the public waters from an underground source. In upholding the trial court's decision, the New Mexico Supreme Court found no law "permitting the storing of private waters in established underground water basins."[44] Thus, in effect, the court refused to recognize the legal right of any landowner to store water through incidental recharge.[45]

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[41] <u>Id.</u> at 1134.

[42] For example, the State of Colorado has implemented elaborate recharge facilities in which both injection and recovery activities are closely measured.

[43] 63 N.M. 425, 321 P.2d 200 (1958)

[44] <u>Id.</u> at 428.

[45] <u>Id.</u>

Although neither statutory law nor case law explicitly recognizes incidental recharge as beneficial use, the State Engineer has developed an administrative method by which water users are given "credit" for incidental recharge that results after a water right has been put to beneficial use. This method gives the water user return flow credits so that the user's calculated impact on a hydrologic system is reduced. The administrative acknowledgment of such incidental recharge is a practical reality in New Mexico, but it falls short of the constitutional protection afforded to water that is beneficially used.

Regulation of Water Rights Used for Recharge

The State Engineer's administrative policies of granting return-flow credits and/or requiring "offset" rights for new groundwater appropriations were designated, in effect, to keep New Mexico rivers "whole." However, the purpose of recharge is not to offset the impact of another use, but a means by which water can be "used" to ensure future groundwater supplies. Under current law, New Mexico could distinguish recharge from "offsets" or "return flow credits" and consider it a beneficial use of water that is stored underground.[46]

If groundwater recharge is considered a "beneficial use," the central question becomes, does the State Engineer have the legal authority to regulate recharge activities? The type of surface water rights being used for groundwater recharge may ultimately determine the nature and extent of the State Engineer's jurisdiction over recharge activities. Under existing laws, the State Engineer would likely have jurisdiction over questions of impairment in cases where a surface water right is taken from the stream flow[47] and used for groundwater recharge.[48]

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[46] Although no explicit provision in the Water Code prevents such a distinction, the State Engineer has never explicitly recognized that the "storage" of water is beneficial use. However, the State Engineer is empowered, in some circumstances, to issue permits for water that will not be used for forty years to prevent forfeiture determinations. See N.M. Statutes Ann. 1978 § 72-41-9. In effect, this is a recognition that "storage" is already considered a beneficial use for some users in New Mexico.

Possible impairment of senior surface rights is foreseeable where a surface right with a junior priority is used for groundwater recharge. Less, foreseeable, but equally important, is the possible impairment to others' groundwater rights that may result from recharge activities. For example, groundwater quality may be impaired in instances where contaminated water is used for recharge, or where the chemical structure of well soils change as a groundwater table rises.[49] Clearly, if water quality is a concern in any proposed change in use of an existing water right, the State Engineer will analyze the effects on other users as part of his consideration of public welfare and conservation.

Regulation of the Right to Recover Recharge

At some point, a recharging entity will wish to recover and use the water it has placed in a groundwater aquifer. As discussed above, appropriated water is private water until it co-mingles with the

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[47] Since the State Engineer treats all surface water in the state as fully appropriated, this article will not hypothesize the legal viability of using unappropriated surface water for recharge activities. Some states such as Texas have chosen not to allow recharge from the appropriated flow of streams or water courses. They do, however, allow new appropriations for recharge with storm waters or floodwaters. See Tex. Water Code Ann. § 11.023(c),(d) (West 1988) (Unappropriated storm waters and floodwaters may be appropriated to recharge underground freshwater bearing sands and aquifers in the portion of the Edwards underground reservoir located within Kinney, Uvalde, Medina, Bexar, Comal, and Hays counties if it can be established by expert testimony that an unreasonable loss of state water will not occur and that the water can be withdrawn at a later time for application to a beneficial use. When it is put or allowed to sink into the ground, water appropriated under . . . this section loses its character and classification as storm water or floodwater and is considered percolating groundwater.).

[48] As the State Engineer has no regulatory authority over pre-1907 surface rights at their existing place of use, it is arguable that the State Engineer would have no authority over whether those rights are used for incidental recharge as long as such use constitutes beneficial use. However, under existing law, using pre-1907 rights for active recharge will most likely require an application for transfer of place and purpose of use and/or change in point of diversion.

[49] Although case law suggests that a water right holder does not have a right to a certain quality of water, See, e.g., Ensenada Land and Water Association et al. v. Sleeper, 107 N.M. 494, 499, 760 P.2d 787, 792 (1988)("as a matter of law, water rights do not include a right to receive a traditional or historical amount of silt carried in the water."); and Stokes v. Morgan, 101 N.M. 195, 680 P.2d 335 (1984)(deterioration of water quality is not necessarily impairment), water quality impairment is a real concern for existing groundwater right holders. N.M. Stat. Ann. 1978 § 72-12-28 provides that an existing water user whose water supply has been made non-potable can sue for relief in district court.

public water supply. Thus, under current law, a water right used for recharge would remain a private right as long as the owner could demonstrate that the water had not reached the public source and that he retained "control" over the water.[50] The relevant issues for the recharging entity then become its ability to exercise dominion and control over recharged water; identification and measurement of the amount of water that is recoverable; and the ability to recover the water without impairing existing rights.

The issue of dominion and control of one's water right was specifically examined in Brantley v. Carlsbad Irrigation Dist.[51] In Brantley, the owner of surface water rights applied for a permit from the State Engineer to drill a supplemental well. The applicant's surface rights were delivered to his property by a twenty-five mile canal. During delivery, an estimated amount of water was "lost" due to seepage into the shallow aquifer. The applicant sought to recapture the lost water and supplement his surface right by drilling a well into the shallow aquifer near the point of his intended use. The court held that "one having a water right in a surface flow, which has thus been lost to the underground reservoir, can neither transfer his surface right nor change his point of diversion to the underground reservoir."[52]

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[50] See e.g., Reynolds v. City of Roswell, 99 N.M. 84 (1982). In Roswell, downstream appropriators protested an application by the City of Roswell to supplement its existing water rights and to change the place of use of the rights. The City had been discharging part of its effluent from a sewage treatment plant into the Rio Hondo and selling the rest to other users. The City contended that it intended to reuse its sewage effluent in its municipal system at some time in the future. The State Engineer approved the City's application but required that it continue discharging the effluent into the river or continue selling treated effluent to other users. The district court disagreed with the State Engineer's decision and held 1) that the City's effluent was private "artificial" water that the City could use as it intended; 2) that neither the appropriators nor the State Engineer could force the City to continue to supply the effluent to others; and 3) that the City had the right to consumptively use all waters appropriated under its water rights. The New Mexico Supreme Court affirmed the district court's conclusion that effluent is private and not public water. However, the court acknowledged that "once the effluent actually reaches a water course or underground reservoir, the City has lost control over the water and cannot recapture it." Id. at 87.

[51] 92 N.M. 280, 587 P.2d 427 (1978).

Thus, it is clear that the right of an owner to recover water that has been "lost" due to such factors as discharge and seepage depends on the owner's ability to show that the water has not reached an underground reservoir. The legal implications for groundwater recharge are obvious. If the goal of groundwater recharge is to secure a more reliable and sustainable groundwater supply, penalizing a water right holder by denying the owner the right to recover all or a portion of the owner's "investment" in groundwater storage frustrates the purpose of recharging activities.[53]

Assuming a recharging entity can satisfy New Mexico's legal requirements of dominion and control, a related concern is whether existing law will protect the recharging entity's "recoverable" water from other users. Like all water rights, the priority of rights used for recharging activities will determine what level of protection they will be afforded vis-a-vis other water users.[54] Moreover, if identifiable measurements of recovery can be ascertained,[55] the state will protect those quantities as any other water right is protected under state law. Without these protections, the recharging entity has less incentive to use a water right for recharge and more incentive to sell and transfer the right at current market rates.

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[52] Id., at 282.

[53] Ironically, if large surface-water irrigation projects were to line their conveyance and drainage systems with concrete, they would be better able to control leakage, resulting in more surface water with which to supply their constituents. However, lining earthen water conveyance systems would decrease incidental recharge and could potentially harm the general aquatic health of an entire basin.

[54] Also, in an effort to protect others' rights, an entity desiring to recover recharge and place it to beneficial use would likely be required to obtain a permit from the State Engineer to change the place and purpose of use of the water right. If reliable measurement techniques are employed during the recharging phase, the impairment of others' water rights at the time of recovery should not, in fact, be at issue.

[55] In administrating recharge recovery, some states require proof of the amount of water that will be recoverable, while others use a complicated formula to determine the amount of water the state will allow to be recovered. See Ariz. Rev. Stat. Ann. § 45-809 (provides a detailed formula for calculating recovery).

Clearly, there are many questions regarding the legal characterization and regulation of recharge activities under existing New Mexico water law. From a legal perspective, the future limitations on recharge and recovery in New Mexico will depend on the legal framework within which these activities are authorized. From a technical standpoint, hydrogeologic characteristics of specific groundwater basins and public policy issues related to the source and nature of the water used for recharge will determine the extent existing water rights can be used for groundwater replenishment.

CHANGES IN LAW AND POLICY TO MAKE RECHARGE A REALITY IN NEW MEXICO

Before New Mexico can realize water conservation through recharge activities, the state must determine the environmental costs and benefits of such activities. Moreover, the use and reuse of New Mexico's water resources and the difference between recoverable and non-recoverable water losses must be investigated and understood before the state can implement laws to govern recharge projects. As a starting point toward encouraging recharge activities, policy makers must understand the sequential use of water and identify where true waste (or avoidable loss) of water occurs within specific hydrogeologic contexts. Only then can legal incentives be formulated to encourage water right holders to engage in recharge activities.

Recognition of Sequential Water Use

Not long ago the popular sentiment among state and federal water administrators was that large irrigation projects need to decrease their conveyance losses by lining their earthen distribution systems. Today, these same administrators are beginning to recognize that large agricultural usage of surface water does not necessarily lead to water "waste" in the legal sense of the term. Although irrigation water is primarily intended for crop consumption, sequential uses of surface water take place in most agricultural settings and such uses may benefit the total water resource. For example, water that runs off irrigated farmland or percolates below crop roots is not wasted from the viewpoint of the total resource if it returns to surface or groundwater supplies. Clearly, water that contributes to shallow groundwater aquifers is not waste but, instead, a readily available and economical water supply source.

The fact that surface-use efficiencies may appear to be low while basin-wide efficiency may be high has led to some confusion in public debates concerning water conservation in New Mexico. New Mexico water administrators must wade through this confusion to identify the true sources of water waste. They must ask the question; "when water moves through a specific hydrological system, how much of it is actually recoverable and how much is nonrecoverable loss of water?" In most cases, the focus will be on identifying non-productive evaporation or seepage and sources of water contamination. Once a new paradigm exists for identifying true water losses, state policy makers can then proceed to effectively implement the legal incentives to encourage water conservation through groundwater recharge.

Legal Incentives For Groundwater Recharge

If the state does not provide legal protection for water rights used for recharge, there is little incentive to engage in recharge activities. This is especially true in the context of active recharge, where the recharging entity will likely incur the costs of constructing recharge facilities. Thus, at a minimum, New Mexico should explicitly recognize that recharge is a beneficial use of water. Without this recognition, water rights used for recharge could be subject to the forfeiture provisions in New Mexico's water code. Another, but less favorable, option would be a legislative exemption from forfeiture determinations. Although this would ensure that water rights used for recharge purposes would not be subject to re-appropriation, a legislative exemption does not rise to the level of the constitutional protection afforded water that is beneficially used.

A related but separate matter is the need for the state to clarify the legal requirement of retaining dominion and control over one's private water. The broad-brushed legal presumption that surface water becomes part of the public supply upon reaching a groundwater aquifer all but slams the door on considering recharge as an option for water conservation. However, sufficient proof that water used for recharge is physically recoverable without harming the public supply or other water users should overcome the presumption that the water right owner lost dominion and control over the recoverable amount.

To encourage incidental recharge from large agricultural projects, the state should explore incentives for continuing to use surface water for irrigation purposes. Water planners and administrators are just beginning to realize that the conversion of irrigated lands to urban uses is resulting in a drastic reduction in incidental recharge to some groundwater aquifers.[56] In addition, the increasing cessation of irrigation may make the operation and maintenance of some irrigation projects cost-prohibitive. One way the state could compensate an irrigation project for its contribution to future water supplies is by granting it recharge "credits" that are subject to recovery by the project beneficiaries or other entities relying on the specific groundwater resource being recharged. Alternatively, the state could empower irrigation projects to levy assessments on entities whose water supplies are benefitted from incidental recharge. Regardless of the type of incentives pursued, the state must realize the importance incidental recharge has played in securing the health of water basins in New Mexico and take steps to ensure that such recharge continues.

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[56] For example, the U.S. Bureau of Reclamation in its 1996 "Middle Rio Grande Water Assessment" claims that loss in irrigated acreage since 1975 has resulted in a reduction of recharge equivalent to the annual water needs of more than 13,000 individuals.

CONCLUSION

For recharge to become a reality in New Mexico, state policy makers must examine the goals of groundwater replenishment within the context of the prior appropriation doctrine. In doing so, they must consider the appropriate balance of potential water savings against possible reductions in surface-flow requirements. To encourage using existing water rights for recharge activities, state law must explicitly recognize recharge as a beneficial use of water entitled to constitutional protection. Without such recognition, there is little incentive for widespread support of groundwater replenishment projects in New Mexico.

WATER RIGHTS TRANSFERS IN NEW MEXICO: THEMES AND CURRENT ISSUES

Charles T. DuMars[57]

New Mexico follows the law of prior appropriation. If you have a water right that is senior to another, that right is given priority in the courts. Furthermore, a New Mexico water right is a property right entitled to protection in the courts from the actions of other property right holders. Finally, that right is a mobile one—the right can be sold and transferred to higher valued uses. This, in theory creates the potential for a "water market" and it is these sales of water to higher valued uses that will serve in part to allow water to be put to higher and more beneficial economic uses. Key to the functioning of this system is the ability to change the place of use of the water right through a "transfer" approved by the State Engineer.

The legal right to transfer a water right is generally the same whether the water is ground or surface, tributary or non-tributary. One exception to this rule is the conjunctive management obligation to maintain an equilibrium between ground and surface water in stream-related aquifers. Water can be transferred from basin to basin, subject to interstate compacts and federal law. Under these systems, the transferor must be certain that within-basin consumptive use after the transfer would not be greater than before the transfer. Simply put, an out-of-basin transfer cannot make the basin worse off than it was before.

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[57] Professor of Law, University of New Mexico School of Law, Albuquerque, New Mexico

A water right priority date remains the same even though it is transferred. Imported water, on the other hand, does not carry a priority date, but is subject to state rules of forfeiture and beneficial use. New Mexico's water rights leasing statute allows temporary transfers, but those transfers and transfers on a permanent basis always go through the Office of the State Engineer. Where a transfer is within irrigation or conservancy districts, and is on lands served by the district works, the state engineer does not get involved so long as downstream users are not affected.

Transfer Procedures

Persons seeking to transfer a water right must file a formal application with the Office of the State Engineer. The application indicates the point of diversion, the place of use, the quantity of the right, and, where they exist, the file number and license number of the right. After filing an application, the applicant publishes a notice of intent to change the right's use or place of use in a newspaper of general circulation where the right is located.

Anyone objecting to a proposed transfer can file a formal protest with the state engineer. Protest must be based on a claim that the transfer will impair existing rights, will be contrary to the conservation of water, or will be detrimental to the public welfare. Where no protest is filed and the state engineer finds the transfer compatible with state law, the transfer application will be approved. Where there is a protest, the state engineer holds a formal, due process hearing on the issues set out in the protest and decides the case. If either party is dissatisfied with the state engineer's decision, he may appeal de novo to the district court. Although such appeals are de novo, case law suggest that courts generally defer to the state engineer's expertise.

In transfer hearings the applicant bears the burden of proving non-impairment, conservation of water, and consistency with the public welfare. Technically, the applicant also must prove the use and amount of the transferred right. Practically, however, where the right has been adjudicated, the protestant bears the burden of disproving the right's use and amount. This is the case because adjudication of rights in a transfer proceedings is not allowed and an existing adjudication decree is accepted as prima facie evidence of the size and validity of the right. Generally, in water right cases the burden of proof is by preponderance of the evidence. If the action filed is a forfeiture or abandonment claim, however, the standard of clear and convincing evidence applies.

Today, when most transfers of water are from irrigation to industrial and municipal uses, quantification by rate of flow and description of the land irrigated is inadequate. The State of New Mexico has for decades officially defined water rights in terms of the number of acre-feet that can be diverted each irrigation season or year. This figure has been determined in the New Mexico Office of the State Engineer by use of the Blaney-Criddle formula, at times as modified, to meet the unique circumstances of the area. Most irrigators have been willing to accept the accuracy of the engineer's determination, or lack the resources to challenge it, so that transfer protests are usually limited to the question of whether or not water has actually been put to beneficial use on the seller's farm.

It could well be that states that have not historically determined the quantum of irrigation water rights in any reliable way, would be spending more money to do so than the resulting increase in market efficiency would justify. However, the process may not be as expensive as it first appears. Instead of analyzing every farm in the state, the New Mexico State Engineer has successfully applied some version of the Blaney-Criddle formula to entire drainage basins that have common soil types, and cropping patterns.

Furthermore, New Mexico has adopted an additional, if small, efficiency. Unlike the Colorado courts, the New Mexico State Engineer has not always individually calculated the losses from each ditch.

All farms in a given area may be allowed the same carriage loss even though individual ditches may differ slightly hydrologically. The result is that individual carriage losses do not have to be calculated in defining the seller's property right. In analyzing an irrigated river valley, the New Mexico State Engineer has not been preoccupied with carriage loss so long as the ditch is not too wasteful. The New Mexico method can reduce the cost of quantification.

The New Mexico law of surface water is nominally prior appropriation law. However, priorities in a great number of instances are not enforced in New Mexico. The reason for this state of affairs is that fewer than half the water rights in the state have ever been adjudicated, so that the state engineer does not have an authoritative priority list on which to base enforcement. The New Mexico State Engineer rarely shuts junior headgates to make water available for senior ditches. What happens instead is a hodge-podge of local customs, proration agreements between ditches and, in some areas, simple, raw taking by those in a physical position to do so.

The only thing that has kept this situation from disintegrating into mayhem or civil war is the fact that—unlike some Western states—New Mexico from an early date has limited the number of rights to water from a given stream. The developer's risk of time and money has not been protected in New Mexico by guaranteeing him a specific place in a priority list; it has been protected by the State's attempt to limit the number and quantity of water rights to a level that the stream could satisfy.

It would seem, at least in theory, that such a system could not exist in a state like Colorado. In Colorado express limitations are not placed upon the number of surface rights. The reliance of Colorado water right owners has been protected by immediate administrative enforcement of priority. One thing is certain. Riparian states that experience water shortages in the future have a different allocation method to consider than just the additional prior appropriation system. The system suggested by the New Mexico experience is a better system for arid and water short regions than prior appropriation.

Although the prior appropriation doctrine in theory lends itself to water rights transfers and a "water market" several practical legal and technical issues complicate the matter.

The first of these is how the State Engineer will define "impairment." Since a right can only be transferred if the transfer does not "impair" another, this is a significant question. Two questions flow from this inquiry:

1) Is the State Engineer willing to provide absolute protection to the other water users on the stream or will a "reasonable ness" standard be applied and in calculating impairment?

2) Will the State Engineer assume the prior appropriation system is in force or will the State Engineer assume prior rights will be treated the same as junior rights in an impairment inquiry?

A hypothetical example illustrates how these questions arise. Suppose a senior water user on the stream proposes to transfer his right upstream of a junior user. Suppose, further the stream has not been adjudicated and that the junior has been taking water out of priority simply because of his upstream position on the stream. Assume further that the downstream senior proposes to sell the consumptive use from his water right to a person upstream of the junior. For the "water market" to function, such a transaction must be possible. Otherwise all senior rights would remain forever at the downstream parts of our stream systems.

An application for transfer of the right upstream is filed and the junior files a protest making three impairment arguments. First, the right cannot be transferred upstream above him because historically, he has received 100 acre-feet of water and if the senior right is transferred upstream of his point of diversion and the new user with the senior priority date begins to take the water (asserts his priority date) the junior will be "impaired" because he will now get less.

A second issue that will arise is, assuming arguendo the right could be transferred upstream, how much should be transferrable? The State Engineer normally allows the transferor to transfer only the amount that was consumptively used at the existing point of diversion. However, if the water historically has been taken upstream by a junior out of priority, could one argue that the amount being transferred should be raised by the amount that was illegally being diverted upstream?

Finally, suppose that the amount to be transferred was 100 acre-feet, but suppose further that by taking the right upstream there has been a saving in carriage loss of 30 acre-feet and suppose further that 100 acre-feet would make less than an acre-foot of actual difference to any one irrigator when the effects of the change are spread among all existing users and all phreatophytes consuming water from the stream system. Should credits be given for water salvaged by moving rights upstream?

And, should there be a de minimis standard for transfers that have no significant impact on any one water user in the stream system? An example of such a calculation is included in Figure 1 below—an exhibit from the Intel applications that was not ruled on by the hearing officer. Note that 1.59 cfs is a measurable amount of water but that the impact on any one irrigator is not.

Turning to the first question—in evaluating impairment, are priorities relevant? The New Mexico Constitution makes "beneficial use" the only basis under which a person can acquire a water right in New Mexico. Granting a water right to an individual for a non-beneficial

APPLICATION NO. 04246 THROUGH 04255 INTO RG-57125, -57125-S, AND -57125-S-2

INTEL TRANSFER EFFECT ON SUPPLY FOR EXISTING USES WITHOUT PRIORITY ADMINISTRATION

DIVERSION POINT	DIVERSION CAPACITY	DEMAND SERVED	RIPARIAN VEGETATION	ALBUQUERQUE AND SAN MARCIAL IRRIGATION SEASON (MARCH-OCT) SUPPLY AFTER COCHITI DAM[5] (CFS)			100-YEAR EFFECT EXISTING REDUCING FLOW BY 1.59 CFS IN DRY SEASON
				WET	MEDIAN	DRY	
Isleta Belen Highlin + Peralta Main	945.6[1] cfs	28786[1] Acres	17000[3] Acres	3300	824	366	0.0014 parts of demand, not measurable
San Acacia Socorro Main	233[1] cfs	15207[1] Acres	8000[3] Acres	3200	880	278	0.0014 parts of demand, not measurable
Bosque del Apache	97[2] cfs	4139[2] Acres	7000[4] Acres	> 2800	> 750	> 202	0.0014 parts of demand, not measurable
	Total	48132 Acres	32000 Acres				

Conclusion:

- Acreage of consumptive use is about 80,000 acres.
- Farm diversion demand for 80,000 acres is about 1140 cfs at 70 acres per cfs; 680 cfs for irrigated lands, and 460 cfs for riparian vegetation. Average consumption for 80,000 acres x 2.1 feet CIR is 160,000 AFY.
- Existing diversions would be affected by a factor of 0.0014 (1.59/1140) of their requirements. The effect would be seen primarily in a change in irrigation efficiencies and an equivalent reduced return flow to the Rio Grande.
- No significant effect on crop consumptive use would be seen from reducing farm deliveries by a few 1000ths of historic supply.
- Flow of less than 100 cfs at Albuquerque sometimes dries up before reaching San Marcial. Higher flows usually are transmitted to Elephant Butte Reservoir.
- The 100-year effect of transfer of 1.59 cfs (1148.994 AFY) without priority administration is summarized below:

Albuquerque Flow Level	Intervening Reach	Elephant Butte Reservoir Contents
Normal, > 400 cfs	No effect	1.59 cfs effect, windfall ends
Low, < 100 cfs	on demand	No effect

1. MRGCD Development Statement, 1980.
2. SEO License #2.
3. RLU0001 GIS File, BOR, 199w
4. RDB0001 GIS File, BOR, 1991 (11,038 acres - 4139 approx. 7000).
5. Wet = exceeded 20% of irrigation season days, median = exceeded 50% of iriagtion season days, dry = exceeded 80% of irrigation season day. Data from U.S. Geological Survey gaging records at Albuquerque, San Acacia and San Marcial.

Figure 1.

use would plainly be unconstitutional. The New Mexico Constitution, also states expressly that priority of appropriation gives the better right to the use of water. To ignore this express language of the constitution would likely be an unconstitutional act by the State Engineer.

A possible answer to this argument would be that this recognition of priority dates should only be carried out by the district courts when enforcing an adjudication. Thus, the State Engineer's only job is to protect all uses from any change in place of use that reduces the available water supply. And, since the majority of our surface water rights are not adjudicated, in those stream systems we follow riparian water law, not prior appropriation law. This is to say, that the person's geographic position on the stream—upstream of another—governs their right to take water, not the prior appropriation doctrine.

To adopt the view that water rights transfers must ignore priority dates would have the most severe policy implications imaginable. Since the "water market" in theory is designed to allow irrigation rights to be conveyed to higher valued uses such as municipal and industrial, then it is imperative that they be transferable. Many transfers would be impossible if priorities were not considered in transfers. In short, in fully allocated streams that experience shortages, such as the Rio Grande, there could be no upstream transfers.

This would be true because in times of shortage, an upstream junior could argue that any transfer above him would mean he would receive less water because historically he had the opportunity to take whatever came to him, even though he took water out of priority, violating the rights of the downstream senior.

Thus, the only development that could occur would be at the bottom of the stream system by transferring rights downstream. Cities like Albuquerque, Rio Rancho and Santa Fe would be unable to move senior water rights upstream to meet their needs. Furthermore, since Rio Grande water rights cannot be transferred below the accounting point on the Rio Grande above Santa Fe, these entities are essentially out of the water market entirely. Thus, whether the State Engineer and the courts allow upstream transfers of senior water rights and uphold the prior appropriation system is critical to New Mexico's water future.

Assuming that the senior right is allowed to be transferred above the junior and the junior can no longer illegally take the senior's water, how much can be transferred? The logical amount would be the senior's historical consumptive supply, but that historical supply has been artificially reduced by the illegal upstream diversion. Should the junior get the rewards of his illegal diversions by having his own illegal diversion constitute the basis for cutting back the senior's right or should the amount of the illegal diversion be added back into the transferable consumptive amount? While in theory the right should be increased, quantification of this amount is not practical, but if it were possible there is no reason to deny the senior this transfer amount.

As to the ability to receive a credit for evaporative and carriage losses that did not occur because the water is to be diverted upstream, there is no logical reason for not allowing this increase if it can be quantified. Certainly, when water is released upstream to a downstream user, the State Engineer includes transportation losses in calculating the amount that will actually arrive at the downstream users headgate.

As to whether there should be a de minimis standard, and how the State Engineer evaluates impairment, there must be some reasonableness standard. In the Intel example, there clearly was no measurable impact on any individual irrigator but there was an impact on the river as a whole. The question turns on what or whom is being protected—the river as a whole, an entire irrigation district, or an individual farmer.

It will be up to the State Engineer and the courts to balance the public interest in allowing transfers in any one case against the cost of denying the transfer and the affirmative benefits to the river and the individual of leaving it in place. This will be the task of the courts and the State Engineers of the next century.

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HOW THE COLORADO SQUAWFISH REELED IN THE ANIMAS-LA PLATA PROJECT: A LEGAL AND INSTITUTIONAL LOOK AT THE ENDANGERED SPECIES ACT

Elizabeth Newlin Taylor[58]

INTRODUCTION

Skillful use of the Endangered Species Act has delayed the Colorado Ute Water Rights Settlement and the Animas-La Plata Project ("ALP") in the Four Corners Region for ten years, driving the costs of the project up and rallying public support against what would be the last big dam in the West. Meanwhile, the communities in Northwest New Mexico and Southwest Colorado, as well as the two Colorado Ute Tribes, have been denied the water promised them by the U.S. Congress. Just this spring, legislation was introduced in the United States Senate and House of Representatives that would allow the ALP to move forward in a revised, smaller fashion. The story of the downsizing of the ALP is a fish tale in the truest sense.

A Brief History of the Animas-La Plata Project

The ALP was authorized as an irrigation project in 1968 as a participating project under the Colorado River Storage Project Act (P.L. 84-485, 1956). Its purpose, in simple terms, was to store water from the Animas River in a reservoir off-channel and then either release that water back into the Animas or pump the water over a ridge, through a tunnel, to the La Plata Basin through the La Plata River. The La

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[58] Attorney, Taylor & Murray, P.C., PO Box 1867, Albuquerque, NM 87103-1867; e-mail: liztaylor@taylormurray.com. Ms. Taylor represents the San Juan Water Commission, a proponent of the Revised Animas-La Plata Project.

Plata Basin contains much fertile, arable land, but not enough water (Interior, 1979). Even on the Animas, which produces much more water, the river's flow varies significantly by season and the Bureau of Reclamation saw a need for a storage project. Most of the water from the Animas passes through the valley during the spring and early summer as run-off from the mountain snowpack. Little water is available in the stream during the dry summer and fall months, when crops need regular moisture to survive (Id.).

The ALP sat on the drawing board of the Bureau of Reclamation for several years after authorization, even though the authorizing legislation said the project would be built at the same time as the Central Arizona Project (P.L. 90-537, 1968). The U.S. Congress appropriated enough money to begin planning the project, but not enough to build it. Then in 1979, the Bureau's Definite Plan Report on the project changed the use of much of the water from irrigation to municipal and industrial (M&I) use for the small towns in Northwest New Mexico and Southwest Colorado (Interior, 1979). The U.S. Fish & Wildlife Service in 1979 even issued an opinion that construction of the project would not jeopardize any endangered species in the river system (Interior, 1996). But still the project languished, and even worse, the towns in New Mexico were prohibited from developing water in the Animas and San Juan River system because the New Mexico State Engineer had issued a permit reserving more than 49,000 acre-feet a year (AFY) for the ALP Project (N.M. State Engineer, 1958). With that reservation of water and other similar reservations, no additional water was available for appropriation and use by the towns.

In the mid-1980s, however, the ALP was revived as the keystone to settling the water rights claims of the two Colorado Ute Indian tribes, the Ute Mountain Ute Tribe and Southern Ute Tribe. In 1986, the tribes and other parties in Colorado settled the tribes' claims on a number of rivers in southwestern Colorado (P.L. 100-585, 1988). On the Animas and La Plata Rivers, the tribes agreed to give up their claims in exchange for irrigation water and M&I water from the ALP. Congress ratified the settlement in the Colorado Ute Indian Water Rights Settlement Act of 1988 (Id.) The time seemed right to launch the ALP. Project proponents even had a groundbreaking ceremony (High Country News, 1996).

The Colorado Squawfish Delays the ALP

Opponents of the ALP found an ally to support their mission in the Colorado Squawfish. The Bureau determined on February 6, 1990, that the ALP might affect the endangered Colorado Squawfish, and reinitiated Section 7 consultation with the U.S. Fish & Wildlife Service (Interior, 1991). The Service's biological opinion concluded that unless water depletions[59] for the ALP were drastically cut back and other steps were taken, the project would jeopardize the Colorado Squawfish and another endangered fish, the Razorback Sucker.

Many of the intended beneficiaries of the ALP signed a Memorandum of Understanding (MOU) with the United States to develop a recovery plan for the fish, which also would allow water development to proceed in the San Juan Basin (Interior, 1991). Perhaps most significantly, the MOU and the Biological Opinion proposed a seven-year research period to allow biologists to study the needs of the endangered fish and determine what level of river flow and other conditions they needed to prosper. In exchange for the seven-year research period and other concessions from the ALP beneficiaries, the Service allowed the depletion of 57,100 AFY for the ALP. While 57,100 AFY is a significant amount of water, it was a decrease of almost two-thirds from the 198,200 AFY depletion anticipated in the full ALP. With that new limit, the Bureau of Reclamation could not begin building the entire ALP. And it certainly could not begin building the project

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[59] A water "depletion" is the amount of water consumed, evaporated or used by plants and lost to the hydrologic system. The amount that can be diverted from a stream generally is a larger number because some of the water returns to the system. The U.S. Fish & Wildlife Service was concemed about limiting depletions because that water is no longer available for the endangered fish.

as a whole until after the seven-year research period had ended and the Service had concluded whether any more water would be available in the system for depletion by the ALP.

The ALP Shifts to an M&I-only Project in Phase I, Stage A

The Bureau had developed a "phased" approach to the ALP that fit this institutional reality. The first phase, called Phase I, Stage A, distributed the allowed 57,100 AFY of depletions to M&I users and postponed building the irrigation facilities until later when, presumably, more water would be available (Interior, 1991). But as the end of the seven-year research period came into view in 1996, it became clear to the ALP beneficiaries that the Bureau could not build the ALP in time to meet the deadline for the settlement of the Colorado Ute Indian Tribes. A deadline in the year 2000 required completed facilities to deliver water to the reservations, or else the tribes could claim their full water rights on the La Plata and Animas Rivers in court (P.L. 100-585). However, construction of the ALP, much less actual delivery facilities, was becoming increasing unlikely.

Moreover, under the strictures of the Endangered Species Act, the water could not be delivered in the amounts and for the purposes needed to satisfy the settlement. Under the Biological Opinion, only 57,100 AFY could be depleted from the system without causing jeopardy to the endangered fish (Interior, 1991). The Bureau had apportioned that 57,100 to M&I uses only, and the tribes' settlement called for 23,800 AFY in irrigation depletions. The tribes' total depletions for all of Phase I were 53,800 AFY. While that was less than the 57,100 AFY available, other entities, notably the San Juan Water Commission in New Mexico, thought they were entitled to the depletion allocated to them in the Bureau's plan. For example, the Bureau had allocated 15,400 AFY to the San Juan Water Commission in Phase I, Stage A. This was enough to allow its member entities, the towns and rural association, to divert the full amount of 30,800 AFY allowed in their state water permit. Given these other demands for the depletions, therefore, the Tribes' settlement could not be met under the limits imposed by the ESA.

Construction also was delayed because the Bureau waited for the biologists to complete their studies and for the U.S. Fish & Wildlife Service to complete a new Biological Opinion. Also, the environmentalists had joined forces with the fiscal conservatives in Congress, and together they formed an increasingly strong force in Congress (High Country News, 1996). The environmental-fiscal conservative coalition was unlikely, but powerful. It particularly appealed to non-western Republicans, who generally do not vote with the environmental lobby. In this case, a Republican, particularly if he was not from the West, could "safely" vote against a new dam and win environmental points, and he could further justify the vote by saying that the ALP had become too expensive. By this time, the estimated cost of the ALP was approaching $700 million, an easy target. In July 1996, for the first time, the U.S. House of Representatives defeated the appropriation the ALP needed to keep the Bureau's planning and environmental studies going. The appropriation was restored after the Senate approved the funding, but the message was clear: The old Animas-La Plata Project could not keep rocking along as it had for years, and something radical had to happen.

Governor Roy Romer Process Initiates Stakeholder Negotiations

In late summer 1996, the ALP proponents approached Colorado Gov. Roy Romer with their problem (High Country News, 1996). Maybe it was time, they suggested, to address head-on the complaints about the ALP. The opponents said the ALP was too expensive, too environmentally damaging, and it could not settle the Indian water rights claims as long as depletions were limited for all practical purposes by the ESA to 57,100 AFY of M&I water. Governor Romer agreed to help set up discussions with all the stakeholders, including the Environmental Protection Agency, the Department of the Interior, the states of New Mexico and Colorado, the ALP's beneficiaries, and its opponents.

He and his team quickly involved Secretary of the Interior Bruce Babbitt, who is the designated trustee for the Indians and as such bears the responsibility to help them complete their Settlement. Also, Secretary Babbitt had been successful in bringing together long-time enemies in other natural resource issues in the West, such as the grazing roundtable in 1994 in Colorado. The Romer team hoped that Babbitt could facilitate a successful resolution in this case. Governor Romer also enlisted his Lieutenant Governor, Gail Schoettler, who had similarly helped resolve long-standing disputes in Colorado through a stakeholder negotiation process.

The first Romer-Schoettler meeting was October 9, 1996, in a Denver suburb. After a few more meetings in the fall and winter, it became clear that the ALP proponents still wanted a new reservoir at Ridges Basin, and the opponents did not (Bell, 1997). A Bureau of Reclamation study in early 1997 completed for the process showed that neighboring reservoirs and stream systems did not have enough "excess" water to satisfy the Ute Indian settlement amounts (Interior, 1997). Thus, the proponents argued, a reservoir was required. Ironically, in 1995, the Sierra Club had commissioned its own study of alternatives to the ALP. One possibility advanced was the use of a downsized Ridges Basin Reservoir and the improvement of two other existing reservoirs to provide the tribes with the necessary water (Hydrosphere, 1995). In the Romer-Schoettler process, however, the opponents, including the Sierra Club, opposed any solution that included a dam and reservoir. In Spring 1997, Lt. Gov. Schoettler challenged each side to come up with a proposal that would fulfill the Indian Water Rights Settlement and provide water for the non-Indians who were relying on the year-round supply promised by the ALP.

ALP Proponents Announce Revised, Downsized ALP

The ALP proponents worked to develop a revised ALP that would meet the twin constraints of limited depletions while still providing enough water to meet the needs of the tribes and other proponents.

The ALP proponents announced their plan in July 1997 (Bell, 1997). The revised ALP met the institutional and legal constraints imposed by the ESA, and it was a compromise that was acceptable politically. Essentially, the revised ALP plan shelves irrigation and shifts water to the two Ute Tribes. The Tribes still take less water over all, about two-thirds of their anticipated depletions, but with their allocation of 33,050 AFY to be split equally, they receive the large majority of the 57,100 AFY. The Tribes also shifted the use of the water from a mixture of irrigation and M&I to all M&I. The Tribes agreed that these smaller amounts of water would be enough to settle their water rights claims. But in return, the Tribes wanted their cost of the project to be waived.

The non-Indian M&I users also agreed to take less than they were allocated in the Bureau's Phase I, Stage A approach. The San Juan Water Commission, for example, cut its amount by about a third, from 15,400 AFY to 10,400 AFY of depletions. That amount is enough to allow the towns and rural associations to use the permits they have, but it completely cuts out the depletions necessary to use the 10,000-AFY reserve of water held in the Commission's name. The Commission and the other non-Indian water users still will pay their cost-sharing amounts required under contracts with the Bureau of Reclamation. The plan also uses as much as possible the configuration of the ALP outlined in the 1996 Final Supplement to the Final Environmental Statement (Bureau, 1996), which found the effects of Phase I, Stage A of the ALP were acceptable. The U.S. Fish & Wildlife Service, in its 1996 Final Biological Opinion, found that the 57,100 in depletions and the facilities necessary to deliver the water as an M&I supply would not jeopardize the endangered fish (Interior, 1996). By eliminating the irrigation facilities and making other changes, the cost of the project also drops significantly, from about $700 million to about $260 million.

Legislation Necessary to Change Tribal Water Settlement

The legislation proposed in March 1997 by Sen. Ben Nighthorse Campbell, S. 1771, enacts the Revised ALP proposed as a result of the Romer-Schoettler Process. The legislation, which is attached as an appendix, is required primarily to change the terms of the Colorado Ute Water Rights Settlement Act (U.S. Senate, 1998).

Following is a summary of the bill's main provisions. The proposed legislation allows the Ute Tribes to agree to less water as full settlement of their claims. The legislation also provides that in exchange for taking less water, the capital costs will be waived. The bill directs the Secretary of the Interior to build the three facilities analyzed and approved in the 1996 Final Supplement to the Final Environmental Statement - the Ridges Basin Reservoir, the inlet conduit to transport water from the Animas River to the reservoir, and the pumping plant. The bill proposes that non-Indian water users pay in accordance with their allocations described in the 1986 Cost Sharing Agreement, which is a component of the 1986 Colorado Ute Water Rights Settlement Agreement. The San Juan Water Commission would pay $8.6 million in up front payments, and the Animas-La Plata Conservancy District would pay $4.4 million in up front payments. The State of Colorado's 1986 cost-sharing commitment to assist in repayment of the agricultural capital obligation is changed, and some $16 million becomes an up front payment for the three facilities.

The legislation authorizes the Secretary to supply small agricultural water allocations to the irrigation districts involved, even though no irrigation facilities are included in the proposed amendments. The legislation provides that in the event additional depletions are permitted for the ALP under the Endangered Species Act, the Secretary is authorized to supply such depletions among the project beneficiaries in accordance with allocations agreed to by the parties. Additional depletions are contemplated in the San Juan River Basin under the existing San Juan River Recovery Program established under the Endangered Species Act.

The legislation authorizes the Secretary, upon the request of the State Engineer of New Mexico, to transfer to the beneficiaries the water permit allocated to the ALP contained in New Mexico Permit No. 2883. Under reclamation law the beneficial owners of the water right are the beneficial users, including the San Juan Water Commission. The transfer of the permit simply provides these entities with legal title to match their present beneficial title. The transfer of the permit shall not change the water right's purpose.

The legislation seeks to put to rest a decade of expensive and duplicative environmental and cultural resource activities associated with the ALP. The voluminous documents already produced on essentially this Revised ALP concluded that depletions and facilities permitted by the Endangered Species Act are sufficiently limited that no material impacts will occur. Therefore, the legislation seeks an approval of the existing environmental and cultural analysis. Given the local opposition to implementing the 1988 Settlement Act through the ALP and given the changing water-development priorities of the Clinton Administration, the Tribes and non-Indian parties contend that Congress must, through a finding of sufficiency, inform federal agencies and the environmental community that the agreement to take sharply reduced depletions and facilities puts an end to the ten-year debate on how to satisfy the 1988 Settlement Act.

The legislation changes a small part of the 1988 Settlement Act, and all other provisions of that act remain intact. The essential purpose of the legislation is to change the conditions that trigger a settlement of the Tribes' water right claims. The change allows the claims to be fulfilled under the existing legal and institutional constraints imposed by the Endangered Species Act.

CONCLUSIONS

The Colorado Squawfish has successfully been used to significantly trim back the Animas-La Plata Project, including the water rights settlement of two Colorado Ute Indian Tribes. After a decade of working to implement their settlement, the Tribes and their fellow beneficiaries initiated a process to try to reach a compromise and address concerns about the Animas-La Plata Project. The process, called the Romer-Schoettler Process, provided a framework for the beneficiaries to revise the project so it would meet existing institutional and legal pressures. The U.S. Congress must enact the result, and legislation has been introduced to accomplish this purpose.

APPENDIX

105th CONGRESS

2d Session

S. 1771

To amend the Colorado Ute Indian Water Rights Settlement Act to provide for a final settlement of the claims of the Colorado Ute Indian Tribes, and for other purposes.

IN THE SENATE OF THE UNITED STATES

March 17, 1998

Mr. CAMPBELL (for himself and Mr. ALLARD) introduced the following bill; which was read twice and referred to the Committee on Indian Affairs

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A BILL

To amend the Colorado Ute Indian Water Rights Settlement Act to provide for a final settlement of the claims of the Colorado Ute Indian Tribes, and for other purposes.

Be it enacted by the Senate and House of Representatives of the United States of America in Congress assembled,

SECTION 1. SHORT TITLE; FINDINGS.

(a) SHORT TITLE- This Act may be cited as the "Colorado Ute Settlement Act Amendments of 1998".

(b) FINDINGS- Congress finds that in order to provide for a full and final settlement of the claims of the Colorado Ute Indian Tribes, the Tribes have agreed to reduced water supply facilities.

SEC. 2. DEFINITIONS.

In this Act:

(1) AGREEMENT- The term "Agreement" has the meaning given that term in section 3(1) of the Colorado Ute Indian Water Rights Settlement Act of 1988 (Public Law 100-585).

(2) ANIMAS-LA PLATA PROJECT- The term "Animas-La Plata Project" has the meaning given that term in section 3(2) of the Colorado Ute Indian Water Rights Settlement Act of 1988 (Public Law 100-585).

(3) DOLORES PROJECT- The term "Dolores Project" has the meaning given that term in section 3(3) of the Colorado Ute Indian Water Rights Settlement Act of 1988 (Public Law 100-585).

(4) TRIBE; TRIBES- The term "Tribe' or 'Tribes" has the meaning given that term in section 3(6) of the Colorado Ute Indian Water Rights Settlement Act of 1988 (Public Law 100-585).

SEC. 3. AMENDMENTS TO THE COLORADO UTE INDIAN WATER RIGHTS SETTLEMENT ACT OF 1988.

(a) RESERVOIR; MUNICIPAL AND INDUSTRIAL WATER- Section 6 (a) of the Colorado Ute Indian Water Rights Settlement Act of 1988 (Public Law 100-585) is amended to read as follows:

"(a) RESERVOIR; MUNICIPAL AND INDUSTRIAL WATER-

"(1) IN GENERAL- After the date of enactment of the Colorado Ute Settlement Act Amendments of 1998, the Secretary shall provide—

"(A) for the construction, as components of the Animas-La Plata Project, of—

"(i) a reservoir with a storage capacity of 260,000 acre-feet; and

"(ii) a pumping plant and a reservoir inlet conduit; and

"(B) through the use of the project components referred to in subparagraph (A), municipal and industrial water allocations in such manner as to result in allocations—

"(i) to the Southern Ute Tribe, with an average annual depletion of an amount not to exceed 16,525 acre-feet of water;

"(ii) to the Ute Mountain Ute Indian Tribe, with an average annual depletion of an amount not to exceed 16,525 acre-feet of water;

"(iii) to the Navajo Nation, with an average annual depletion of an amount not to exceed 2,340 acre-feet of water;

"(iv) to the San Juan Water Commission, with an average annual depletion of an amount not to exceed 10,400 acre-feet of water; and

"(v) to the Animas-La Plata Conservancy District, with an average annual depletion of an amount not to exceed 2,600 acre-feet of water.

"(2) TRIBAL CONSTRUCTION COSTS- Construction costs allocable to the Navajo Nation and to each Tribe's municipal and industrial water allocation from the Animas-La Plata Project shall be nonreimbursable.

"(3) NONTRIBAL WATER CAPITAL OBLIGATIONS-
The nontribal municipal and industrial water capital repayment obligations for the Animas-La Plata Project shall be satisfied, upon the payment in full—

"(A) by the San Juan Water Commission, of an amount equal to $8,600,000;

"(B) by the Animas-La Plata Water Conservancy District, of an amount equal to $4,400,000; and

"(C) by the State of Colorado, of an amount equal to $16,000,000, as a portion of the cost-sharing obligation of the State of Colorado recognized in the Agreement in Principle Concerning the Colorado Ute Indian Water Rights Settlement and Animas-La Plata Cost Sharing that the State of Colorado entered into on June 30, 1986.

"(4) CERTAIN NONREIMBURSABLE COSTS- Any cost of a component of the Animas-La Plata Project described in paragraph (1) that is attributed to and required for recreation, environmental compliance and mitigation, the protection of cultural resources, or fish and wildlife mitigation and enhancement shall be nonreimbursable.

"(5) TRIBAL WATER ALLOCATIONS-

> "(A) IN GENERAL- With respect to municipal and industrial water allocated to a Tribe from the Animas-La Plata Project or the Dolores Project, until that water is first used by a Tribe or pursuant to a water use contract with the Tribe, the Secretary shall pay the annual operation, maintenance, and replacement costs allocable to that municipal and industrial water allocation of the Tribe.
>
> "(B) TREATMENT OF COSTS- A Tribe shall not be required to reimburse the Secretary for the payment of any cost referred to in subparagraph (A).

"(6) REPAYMENT OF PRO RATA SHARE- As an increment of a municipal and industrial water allocation of a Tribe described in paragraph (5) is first used by a Tribe or is first used pursuant to the terms of a water use contract with the Tribe—

> "(A) repayment of that increment's pro rata share of those allocable construction costs for the Dolores Project shall commence by the Tribe; and
>
> "(B) the Tribe shall commence bearing that increment's pro rata share of the allocable annual operation, maintenance, and replacement costs referred to in paragraph (5) (A).".

(b) REMAINING WATER SUPPLIES- Section 6 (b) of the Colorado Ute Indian Water Rights Settlement Act of 1988 (Public Law 100-585) is amended by adding at the end the following:

"(3) At the request of the Animas-La Plata Water Conservancy District of Colorado or the La Plata Conservancy District of New Mexico, the Secretary shall take such action as may be necessary to provide, after the date of enactment of the Colorado Ute Settlement Act Amendments of 1998, water allocations—

"(A) to the Animas-La Plata Water Conservancy District of Colorado, with an average annual depletion of an amount not to exceed 5,230 acre-feet of water; and

"(B) to the La Plata Conservancy District of New Mexico, with an average annual depletion of an amount not to exceed 780 acre-feet of water.

"(4) If depletions of water in addition to the depletions otherwise permitted under this subsection may be made in a manner consistent with the requirements of the Endangered Species Act of 1973 (16 U.S.C. 1531 et seq.), the Secretary shall provide for those depletions by making allocations among the beneficiaries of the Animas-La Plata Project in accordance with an agreement among the beneficiaries relating to those allocations.".

(c) MISCELLANEOUS- Section 6 of the Colorado Ute Indian Water Rights Settlement Act of 1988 (Public Law 100-585) is amended by adding at the end the following:

"(i) TRANSFER OF WATER RIGHTS- Upon request of the State Engineer of the State of New Mexico, the Secretary shall, in a manner consistent with applicable State law, transfer, without consideration, to the New Mexcio Animas-La Plata Project beneficiaries or the New Mexico Interstate Stream Commission all of the interests in water rights of the Department of the Interior under New Mexico Engineer permit number 2883, Book M-2, dated May 1, 1956, in order to fulfill the New Mexico purposes of the Animas-La Plata Project.

"(j) TREATMENT OF CERTAIN REPORTS-

"(1) IN GENERAL- The April 1996 Final Supplement to the Final Environmental Impact Statement, Animas-La Plata Project issued by the Department of the Interior and all documents incorporated therein and attachments thereto, and the February 19, 1996, Final Biological Opinion of the United States Fish and Wildlife Service, Animas-La Plata Project shall be considered to be adequate to satisfy any applicable requirement under the Endangered Species Act of 1973 (16 U.S.C. 1531 et seq.), the National Environmental Policy Act of 1969 (42 U.S.C. 4321 et seq.) or the Federal Water Pollution Control Act (33 U.S.C. 1251 et seq.) with respect to—

"(A) the amendments made to this section by the Colorado Ute Settlement Act Amendments of 1998;

"(B) the initiation of, and completion of construction of the facilities described in this section; and

"(C) an aggregate depletion of 57,100 acre-feet of water (or any portion thereof) as described and approved in that biological opinion.

"(2) STATUTORY CONSTRUCTION- Nothing in this subsection shall affect—

"(A) the construction of facilities that are not described in this section; or

"(B) any use of water that is not described and approved by the Director of the United States Fish and Wildlife Service in the final biological opinion described in paragraph (1).

"(k) FINAL SETTLEMENT-

"(1) IN GENERAL- The provision of water to the Tribes in accordance with this section shall constitute final settlement of the tribal claims to water rights on the Animas and La Plata Rivers.

"(2) STATUTORY CONSTRUCTION- Nothing in this section may be construed to affect the right of the Tribes to water rights on the streams and rivers described in the Agreement, other than the Animas and La Plata Rivers, to participate in the Animas-La Plata Project, to receive the amounts of water dedicated to tribal use under the Agreement, or to acquire water rights under the laws of the State of Colorado.

"(3) ACTION BY THE ATTORNEY GENERAL- The Attorney General of the United States shall file with the District Court, Water Division Number 7, of the State of Colorado such instruments as may be necessary to request the court to amend the final consent decree to provide for the amendments made to this section under section 2 of the Colorado Ute Settlement Act Amendments of 1998.".

SEC. 4. STATUTORY CONSTRUCTION; TREATMENT OF CERTAIN FUNDS.

(a) IN GENERAL- Nothing in the amendments made by this Act to section 6 of the Colorado Ute Indian Water Rights Settlement Act of 1988 (Public Law 100-585) shall affect—

(1) the applicability of any other provision of that Act;

(2) the obligation of the Secretary of the Interior to deliver water from the Dolores Project and to complete the construction of the facilities located on the Ute Mountain Ute Indian Reservation described in—

(A) the Department of the Interior and Related Agencies Appropriations Act, 1991 (Public Law 101-512);

(B) the Department of the Interior and Related Agencies Appropriations Act, 1992 (Public Law 102-154);

(C) the Department of the Interior and Related Agencies Appropriations Act, 1993 (Public Law 102-381);

(D) the Department of the Interior and Related Agencies Appropriations Act, 1994 (Public Law 103-138); and

(E) the Department of the Interior and Related Agencies Appropriations Act, 1995 (Public Law 103-332); or

(3) the treatment of the uncommitted portion of the cost-sharing obligation of the State of Colorado referred to in subsection (b).

(b) TREATMENT OF UNCOMMITTED PORTION OF COST-SHARING OBLIGATION- The uncommitted portion of the cost-sharing obligation of the State of Colorado referred to in section 6(a) (3) of the Colorado Ute Indian Water Rights Settlement Act of 1988 (Public Law 100-585), as added by section 3 of this Act, remains available after the date of payment of the amount specified in that section and may be used to assist in the funding of any component of the Animas-La Plata Project that is not described in such section 6(a)(3).

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WATER POLITICS IN SOUTHERN NEW MEXICO

Gary L. Esslinger[60]

INTRODUCTION

Irrigation of land in New Mexico has been influenced considerably by laws and customs of Indian, Spanish and Mexican cultures. Throughout history, water has dictated the course of human events in the arid Southwestern desert. Native Americans, Spanish colonists and all those who followed have based settlement patterns, agricultural practices and commerce networks on the availability of this precious resource. Disputes over water have led to wars, gun battles and court actions, some of which persist to this day.

Rapid urbanization in the Southwest has made water allocation and utilization problems even more acute in recent years, especially along the U.S.-Mexico border. As known water reserves become depleted, and fewer areas with new supplies are discovered, competition over existing sources will increase. This has created an atmosphere in which various political, economic and social entities feel they must fight to safeguard their individual interests.

Recent events in the Lower Rio Grande Basin (LRG) region of Southern New Mexico illustrate this conflict. The LRG includes that section of the river valley shared by Las Cruces and Doña Ana County in New Mexico. Immediately adjacent to the LRG on the other side of the Texas-New Mexico border is El Paso, Texas, and Ciudad Juárez in Chihuahua, Mexico, which share the common groundwater basins

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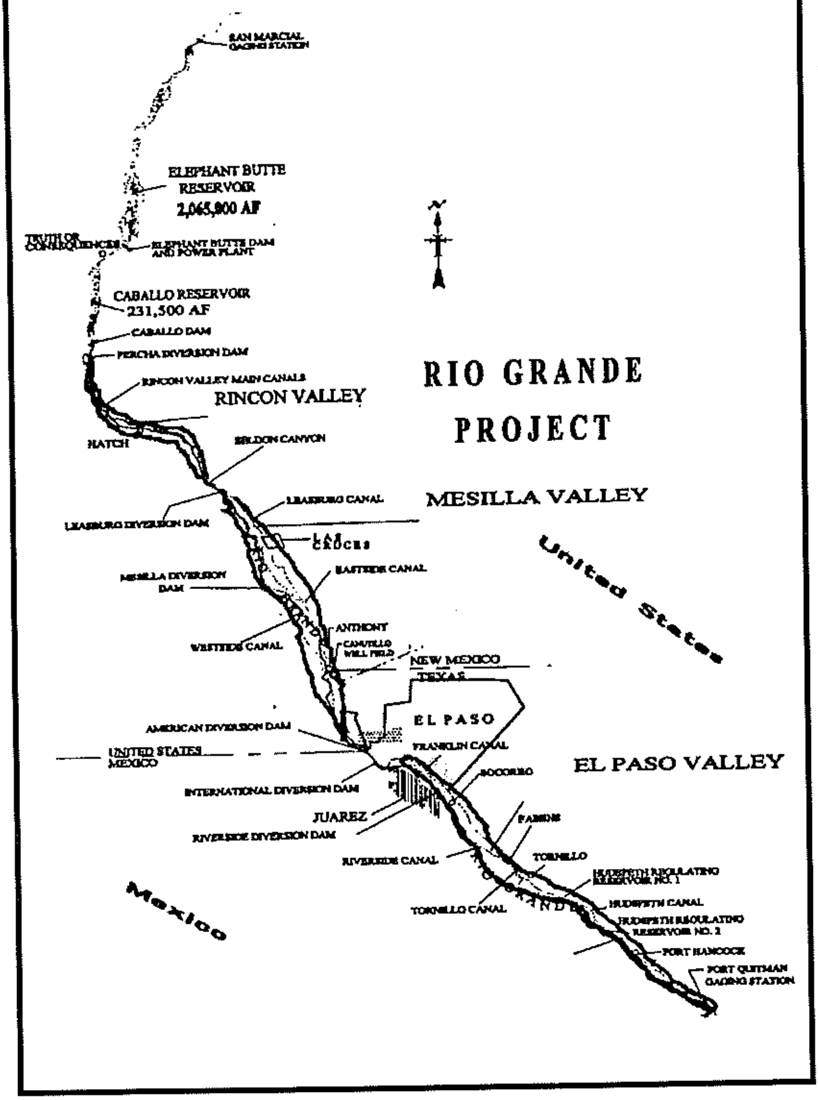
[60] Treasurer-Manager of the Elephant Butte Irrigation District located in Las Cruces, New Mexico. This paper reflects the views and observations of the author and is not an official position of the Elephant Butte Irrigation District.

Bureau of Reclamation, February 1998



and the Rio Grande. This paper will examine various aspects of area water disputes, describe the legal framework within which some disputes have been resolved and study the prospects of the Elephant Butte Irrigation District's goals to manage its water resources in the future.

The evolution and operation of the Elephant Butte Irrigation District (District) is of interest and importance to the agricultural sector of Southern New Mexico and the State of New Mexico as a whole. Prior to the Rio Grande Project, irrigation within the Rincon and Mesilla Valleys was carried out by direct diversion from the river through a system of community ditches. The District's current distribution system could be the basis to begin the transformation of historic agricultural use of water to a growing municipal use.

Section I provides a jurisdictional backdrop and an analysis of some problems related to water allocation in Southern New Mexico. Section II is a history of the water politics in the Lower Rio Grande. Section III describes the legal framework of the entities that may be involved in conflicts over water and also describes the legal framework of a stream adjudication.

SECTION I

JURISDICTIONAL OVERVIEW OF WATER ALLOCATION IN THE LOWER RIO GRANDE BASIN

The Legal Parameters

This paper focuses on the Lower Rio Grande Basin (LRG) located in Southern New Mexico which includes the headwaters of the Elephant Butte Reservoir south to Ft. Quitman, Texas, and is known as the Rio Grande Project.[61] Rio Grande water issues in this stretch of the river

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[61] The New Mexico State Engineer has designated the Lower Rio Grande Basin to cover the area from the Caballo Reservoir to the NM-Texas border. This paper will expand that area to recognize the area covered by the Rio Grande Project.

involve two different nations—the United States and Mexico, and the laws of four different states—Chihuahua, Colorado, New Mexico and Texas. The allocation of water is governed by international treaty, a tri-state compact, federal reclamation laws, state statutes and numerous contracts. The Rio Grande Reclamation Project Act (which approved the Rio Grande Project) was passed by Congress on February 25, 1905 (33 Stat. 814). The 1906 International Treaty with Mexico entitled it to an annual delivery of 60,000 acre-feet of Rio Grande water (34 Stat 2953). The Rio Grande Compact, a tri-state agreement between Colorado, New Mexico and Texas, was approved by Congress in 1939 (53 Stat 785). The Rio Grande Project encompasses the waters of the Elephant Butte Reservoir south to Ft. Quitman Texas.

The Players

UNITED STATES – There is no national policy for groundwater apportionment. These public management questions are usually left to individual states. Interstate Reclamation projects, such as those on the Rio Grande and the Colorado River, where the federal government funds basic infrastructure, utilize interstate compacts to govern water usage. The U.S. government will argue, however, that they must be involved with any solution over reallocation of water in the Lower Rio Grande Basin, if for no other reason than any solution will require federal supervision.

TEXAS – Texas is in its infancy enacting groundwater regulations. Despite possible shortages in the state's major aquifers, especially the Ogallala Aquifer under the High Plains and the Edwards Aquifer near San Antonio, the legislature has been reluctant to adopt laws to control groundwater usage. Texas subscribes to the English right-of-capture rule allowing well owners to use the water in any way they choose. The only restriction is that usage must not cause a neighbor's property to sink. An effort in 1993 to manage the Edwards Aquifer suggests that groundwater management issues will have to be resolved by the courts. A stumbling block for efforts to establish statewide water policy is that East Texas has too much water while West Texas has too little.

NEW MEXICO – New Mexico has a comprehensive groundwater regulatory system which is based on the doctrine of prior appropriation. Derived from Spanish law, this doctrine contains two central principles.

1. the first user (appropriator) has the right to take and use the water; and
2. that right continues as against subsequent users as long as the appropriator puts the water to beneficial use.

Each appropriator under this doctrine establishes a priority according to when and how much, water was first used. There is no provision for judging the relative benefit each user of a shared source derives, or seeks to derive, from the water use. In times of shortage, the newest users are the first to be denied water, regardless of the relative merit of their need. This approach creates an incentive to each land owner to protect himself against his neighbor's acts by putting to beneficial use as much of the resource as quickly as possible. Therefore, there is an economic incentive for over-investment and for depletion, rather than for conservation of the resource.

MEXICO – Mexico is currently undergoing sweeping economic, social and political changes that make it difficult to describe its legal mechanism for water policy and management decisions. Recent amendments to their water laws have eased restrictions on use, ownership and foreign control of agricultural land and have led to a need for revisions in water policy. The revisions seek to "guarantee the conservation of water for social welfare and for industrial, agricultural and services production ..." and "... to create a more rational use of water and preserve its quality." It adheres to the principal that "national waters" belong to the state–hence to the people of Mexico.

SECTION II

HISTORY OF WATER POLITICS IN THE LOWER RIO GRANDE BASIN

Elephant Butte Irrigation District's Rights and Interests in the Lower Rio Grande Basin

On December 22, 1904, the Elephant Butte Water Users Association was formed to provide for and distribute to the lands of the holders of shares of the association, to which the shares and the rights and interests represented are appurtenant, an adequate supply of water for the irrigation of such lands. The Association was also formed to divert water within the Territory of New Mexico, to pump water from underground sources, and to carry and distribute that water for the irrigation of lands of the holders of shares and to enter into any contract with the United States Government to acquire and construct the necessary facilities. The ownership of a share of stock in the Association carried with it the right to have delivered a proportionate amount of all stored and developed water.

The Rio Grande Project was authorized on February 25, 1905 as a Bureau of Reclamation Project under the authority of the Reclamation Act of 1902 to construct a dam on the Rio Grande as part of a general system of irrigation.

On June 27, 1906, the Elephant Butte Water Users Association and the El Paso Valley Water Users Association entered into a "Construction Contract" with the United States. This contract obligated the individual shareholders for the building of the irrigation works of the Rio Grande Project and also to pay the costs of yearly maintenance and operation. The 1906 contract recognized that the rights to the use of water from the proposed irrigation works would be appurtenant to the designated lands owned by the shareholders.

The United States did subsequently appropriate, for the Rio Grande Project, all of the unappropriated water of the Rio Grande, which was put to beneficial use by the members of the Water Users Association and continues to be put to beneficial use by the constituents of the water user district. The United States, as trustee, made a filing with the Territory of New Mexico to appropriate the water rights for the Project, and would remain the record title holder only until the project construction costs were paid off.

Historically, water distributed by the Elephant Butte Irrigation District (District) has been used for agricultural purposes. As irrigated land has been converted to urban development, the water associated with it has been reassigned to other qualified land within the district. The district has resisted pressure to convert the associated water to nonagricultural uses because the agricultural demand remains. However, the District also understands that it must address these water management issues with creative thinking and a willingness to address the demands for regional solutions. Under existing New Mexico law the use of district water is permitted outside the existing or current boundary of the district. State law grants the District the power to lease or rent the use of water to occupants of other lands or municipalities within or without the district provided no vested or prescriptive right to the use of the water is attached to the lease (§73-10-16 New Mexico Statutes Annotated).

The District's Board of Directors has held to the position that the District water is to be used strictly for irrigation on lands having district surface water rights appurtenant to the land. Its main goal is to provide water to agriculture.

The District was organized as a quasi municipality or public corporation, and as such it is a political subdivision of the state. Upon the formation of the District in 1919, the EBWUA granted all of its interests to the District by contract. The District also assumed the repayment obligation to the United States for the Construction of the Project.

Under New Mexico law, irrigation districts are given broader powers than the powers granted to water user associations. These broader powers include annexation, taxation, and bond issuance. (See §73-10-1 et. seq. New Mexico Statutes Annotated.) The initial function of the District was to collect revenues from area surface water users to repay the debt owed to the federal government for the construction of the district's irrigation and drainage system. In addition, the District handled relations between area surface water users and the Bureau of Reclamation. All operation and maintenance remained under the control of the Bureau of Reclamation until the district had repaid the construction debt.

The Fact Finders Act of 1924 provided that Reclamation may relinquish all operations and maintenance to an irrigation district. In 1971 when the district repaid the construction debt owed to the federal government, negotiations began which detailed the transfer of the operation and maintenance from the Bureau of Reclamation to the District. In 1992 the District also received certification of title and ownership of District facilities.

Federal Presence in the Lower Rio Grande Basin

On February 25, 1905, Congress authorized the building of the Rio Grande Project to serve New Mexico and Texas. The Elephant Butte Water Users Association and El Paso Water Users Association were formed to contract with the United States to build the project. Elephant Butte Dam was completed in 1916 and stores fifty-seven percent of the water for use within Elephant Butte Irrigation District (District) and forty-three percent for use in Texas by the El Paso County Water Improvement District #1.

Under Section 8 of the Reclamation Act, the United States must apply to the states for water which will be used in its reclamation projects. The Reclamation Service (now the Bureau of Reclamation) gave notice to the New Mexico Territorial Engineer (now the New Mexico

State Engineer) in 1906 that the federal government intended to appropriate 730,000 acre-feet of water per year from the unappropriated waters of the Rio Grande, which water would be impounded for the Rio Grande Project in Texas and New Mexico. In 1908 an additional filing was made to appropriate all of the unappropriated waters of the Rio Grande and its tributaries.

Additionally, the United States must make sure that Mexico receives 60,000 acre-feet of water annually as the result of the 1906 Mexican Treaty. This water, which is stored in Elephant Butte Reservoir, must be delivered to the Acequia Madre near El Paso, Texas.

The United States has taken the position that neither the New Mexico State Court nor the Texas Administrative Judge have jurisdiction over the United States for the adjudication of the water rights of the Project. The jurisdictional challenge is based on failure of the proceedings to satisfy the requirements of the McCarran Amendment found at 43 U.S.C. § 666, because neither adjudication addresses the entire river system. Substantively, it is the United States position that the federal government interests in the use of Project water can only be adjudicated in Federal court. It agrees that the water laws of New Mexico and Texas must be complied with, but only so long as those laws are not inconsistent with federal law.

New Mexico Water Rights in the Lower Rio Grande Basin

New Mexico, like most western states, adopted the prior appropriation doctrine with respect to the acquisition of water rights. Basically, the doctrine means that the first appropriator of water in time has the better right in times of shortage. This contrasted greatly with the riparian system in the east where all water users share equally in times of shortage.

New Mexico Statutes authorize the creation of two different types of water organizations to manage surface water: conservancy and irrigation districts. Within the context of a conservancy or irrigation district, a water right holder is an individual who has been issued the right to use surface water within an irrigation or conservancy district. The water right holder does not own the corpus or body of water used in the irrigation of cropland, rather he owns the right to use the surface water.

Although irrigation and conservancy districts are both formed by water right holders, the reasons behind each are different. In 1919 New Mexico enacted comprehensive irrigation district laws as an amendment to an earlier 1909 irrigation law. It provided for the voluntary organization of landowners and irrigators into irrigation districts. The 1919 law included special provisions authorizing cooperation of New Mexico irrigation districts with the federal government under the Reclamation Law of 1902 and mandates that irrigation districts cooperate closely with the federal government under Federal Reclamation Law. (See §73-10-1 et seq. New Mexico Statutes Annotated.) Irrigation districts have been formed primarily for the management and allocation of surface water. The major irrigation districts formed in cooperation with the United States under Reclamation laws are the Carlsbad Irrigation District, the Bloomfield Irrigation District, and the Elephant Butte Irrigation District.

Water in New Mexico is under the regulatory authority of the Office of the State Engineer. The State Engineer is responsible for the enforcement of water right priorities as well as administrative control of all water basins. It was not until September of 1980 that the State Engineer took administrative control over our basin, which was designated as the Lower Rio Grande Basin (LRG).

New Mexico law provides that water may be appropriated, or taken for use, on the basis of three principles.

1. All surface and groundwater belongs to the public and is subject to appropriation for beneficial use. An appropriator

does not own the water, only the right to divert or impound and use it.

2. Beneficial use is the basis, measure and limit of the right to use water. Agricultural, domestic, recreational, municipal, industrial and other uses are considered beneficial as long as there is no willful waste of water.

3. Priority of appropriation gives the better right. Priority is based upon the date on which construction of works for the beneficial use of water began or on which a notice of intention or an application to appropriate water was filed with the State Engineer. The user with the earliest priority date is entitled to receive a full appropriation before those with later, or junior, priorities receive theirs. This concept is referred to as the doctrine of prior appropriation.

The State Engineer, who is appointed by the Governor and confirmed by the Senate, is responsible for the administration of the State's surface and groundwater according to these principles.

Priority Enforcement

The State Engineer manages the LRG in a format known as a "stream related basin." Basically, he must not only consider the diversion of surface water, but he must also look at the interrelationship between the river (surface water) and the pumping of water (groundwater).

This is in contrast to a non-stream related basin where there is only the pumping of groundwater, i.e., the Hueco Basin. In this situation, the State Engineer calculates the total amount of water in the Basin and then calculates a 40-year life for the water to be pumped out. He reserves a certain amount of water for emergencies and domestic use by individual home owners. He then administers the pumping based on his 40-year calculation. Currently, the State Engineer is trying to decide whether the area east of Interstate 10 on the east mesa near Las Cruces, New Mexico, is within its own basin without any connection to the Rio Grande. If so, this "Jornada Basin" will be administered differently from the stream related Lower Rio Grande Basin. Questions concerning inter-basin transfers of water from the Jornada Basin to the Lower Rio Grande Basin will have to be answered.

The easiest way to understand the Lower Rio Grande Basin, what the State Engineer must monitor, is to imagine a bathtub full of sand that is slightly elevated at one end. If the faucet is turned on, the bathtub will fill until the sand is fully saturated. The water will then flow across the top of the sand and flow out the end of the bathtub. This represents the situation of the Rio Grande, and the groundwater that is stored beneath it. The Rio Grande, over hundreds of years, has stored water in certain formations underneath it.

Now imagine that you put straws in the bathtub's sand and start sucking out water. The water which used to flow across the sand at the top of the bathtub now flows down into the bathtub to fill in the gaps left by the taking of water through each of the straws. The amount of water that used to flow out the end of the bathtub is reduced.

Similarly, the pumping of wells eventually leads to a cone of depression that is filled in by the surface water of the Rio Grande. Water which formerly found its way down the river into Texas and Mexico is now first replacing the water taken by pumps. This is a problem because under New Mexico law, the senior right cannot be affected by a junior user. In other words, the pumping of groundwater may not affect or impair the use of the surface water which is senior in time.

The Pecos River Experience

Years ago the State of Texas sued the State of New Mexico claiming that groundwater pumping in New Mexico had diminished the flows of the Pecos River reaching Texas. The United States Supreme Court, which has original jurisdiction involving one state suing another, agreed with Texas. The State of New Mexico was told to deliver the water it had wrongfully kept from reaching the state line as well as to keep up with its current deliveries.

The State has had to purchase water rights to put into the river to make up the deficit. In addition, it has taken action to curtail groundwater pumping that has occurred in recent decades. It is clear that the State must take a hard look at our existing water use in the LRG to make sure that we do not wind up in the same predicament where water users do not have a valid water right.

On February 26, 1996, State District Judge Harold Byrd entered his opinion regarding ownership of the water rights in the Carlsbad Project. The Court was of the opinion that the beneficial ownership of Project water rights is vested in landowners in the Project measured by the amount of water devoted to beneficial use. Ownership of water rights in the Project are appurtenant to land in the Project upon which they are devoted to beneficial use. Project water rights are not owned by the United States or the Carlsbad Irrigation District (CID). The determination of ownership of Project water rights by members of CID does not preclude adjudication of storage and diversion rights of the US/CID and members of CID and these rights will be determined in the proceedings. The issue of whether it was necessary to adjudicate the elements of Project water rights to landowners individually was deferred at this time and will be determined during the course of subsequent proceedings.

The Court was also of the opinion that the United States and the CID have certain diversion, storage, and distribution rights and interests in Project water. Under the Reclamation Act, the United States has authority to divert, store and distribute Project water for the use and benefit of the appropriating landowner. In addition, the United States and the CID have certain rights and interests in storage and distribution of Project water in order to accomplish the purpose of the Reclamation Act and the Project.

The El Paso Litigation

In 1980 the City of El Paso, through its Public Service Board, filed applications to appropriate over 270,000 acre-feet (1 acre-foot is approximately 325,900 gallons) of water from the LRG and Hueco Basins for use in El Paso. This amount of water equated with the amount of water the District delivers to 90,000 irrigated acres of farm land at three acre-feet per acre. The City of Las Cruces uses approximately 13,000 acre-feet of water per year.

El Paso claimed that there was unappropriated groundwater in the LRG not currently being used by New Mexico that could be taken and put to immediate beneficial use. After eleven years of litigation, the City withdrew its applications primarily based on the District's commitment to help the City more efficiently use the Texas portion of surface water supply out of the Rio Grande Project for municipal purposes. The New Mexico-Texas Water Commission was formed to help implement the court settlement. Thus far, ongoing planning has centered on El Paso accessing project water on a year-round basis and also a better conveyance system that increases water quality and quantity. With these two experiences in mind, the District initiated the stream adjudication process in the LRG.

One of the most recent proposals coming from the Commission is to construct one or several regional water plants south of the Caballo Reservoir in New Mexico and Texas. These plants could provide treated surface water to the cities of Las Cruces and El Paso as well as the numerous small communities, including colonias, in Doña Ana County and El Paso County. With these proposals, there are numerous operational, legal, and environmental hurdles that must be overcome. For example, District farmers are very concerned that any change in operations could affect groundwater pumping for agricultural purposes, affect the agricultural drain system which leaches salts from the soils, and affect return flows to the river.

To date, none of the Rio Grande within the Rio Grande Project has been adjudicated. As a result, there is no priority administration of water use or basis for evaluating the priority of a particular water right. The lack of adjudicated rights precludes the development of a secure market within which to purchase water rights, or the right to use water. Because of the long-term financial planning and cost to construct surface water treatment plants, municipalities need long-term water supply contracts which can provide some degree of certainty as to the priority of the water for which it has contracted. Also, it is imperative for the region to draft a drought management plan providing as much certainty as possible to a priority of uses in the event of severe drought.

SECTION III

THE LEGAL FRAMEWORK OF A STREAM ADJUDICATION

It will be up to the State Engineer to determine how much groundwater may be pumped without impairing the rights of the Rio Grande Project to deliver surface water. The legal mechanism used to prioritize everyone's right to water in the basin is known as a "General Stream Adjudication." In effect, it is a lawsuit which joins all of the water users of a stream system.

In the adjudication, the court sets forth everyone's rights to surface and groundwater. It will determine how much water everyone is entitled to and the priority date of their use. If there is an over-drafting of groundwater by junior users, which is in effect taking surface water, these junior users will be told to stop pumping.

We need to know the extent to which we have water resources available to us now and in the future. We must inventory our legitimate water supplies so we know how much of a sustainable resource we have. Then we can determine how much growth we are willing to support as a community, and what the tradeoff will have to be to support it. The process of taking inventory of legitimate water supplies is called the adjudication process.

The Adjudication Process

New Mexico has adjudicated water rights since the enactment of the surface water code in 1907. A water right adjudication is a process by which the ownership and extent of water rights are determined. It is similar to a quiet title suit to establish the ownership of land.

The adjudication process consists of two phases:

1. A technical one in which a hydrographic survey is performed to identify, map and report the status of water rights in a particular stream system or groundwater basin; and
2. A legal one in which a lawsuit is filed and court orders are issued, stating how much water each entity has a right to divert and use for a specific beneficial purpose.

A hydrographic survey is usually the first step taken in a water rights adjudication. A survey can begin in one of the following two ways:

1. The State Engineer, based upon the direction given him by state law, can decide to conduct a survey to determine the extent of a water supply, plan for its development, or collect in formation for water rights adjudication. The areas chosen by the State Engineer are usually those facing the most critical water allocation problems.

2. A judge can issue a court order for a survey to obtain the information necessary for determining the water rights involved in an adjudication lawsuit.

Before any field work takes place in a survey, the Office of the State Engineer's staff reviews water right records for the survey area and prepares flight line maps for aerial photography. Cropping patterns and crop irrigation requirements are computed. Municipal, industrial, stock and domestic water uses are analyzed. Land ownership is verified with courthouse records. Although a hydrographic survey gathers information on land ownership, it does not establish legal ownership or property boundaries. The investigations only produce evidence on the location, amount and ownership of water rights on irrigated lands.

Following this work, the staff conducts a field check of all water uses and draws maps depicting the areas of water use. The maps and other data are compiled into a report which lists all the known uses of water in the survey area. For each water right the following information is included:

- Owner of the water right
- Purpose of water use
- Priority
- Point of water diversion
- Place of water use
- Amount of acreage irrigated
- Amount of water required for use

The complete report, available to the public upon request, is then sent to the Office of the State Engineer legal staff which begins work on the legal phase of the adjudication process.

This phase starts with the filing of a lawsuit by the State of New Mexico, the federal government or an interested person. In our case, the District brought suit over a decade ago. All water right owners in the affected stream system or groundwater basin are included, or joined, in the suit.

Each water right owner is sent an offer of judgment by the Office of the State Engineer. This document is a proposed agreement between the water right owner and the State which defines what the state believes is:

- The amount of the water right,
- The water right's priority date,
- The place and purpose of water use,
- The point of water diversion,
- The source of water, and
- The ownership of the right.

The water right owner may either accept or reject the offer. Objections are usually resolved through investigations; however, the owner has a right to a court hearing. If a water right owner fails to act within the specified time, the court may issue a default judgment, adjudicating the water right described in the offer. When an offer has been signed by both the state and the owner, the court enters an order confirming the agreement.

When all water rights have been settled between the state and the water right owners, an individual owner or group of owners may challenge the water rights of others. Hearings on any challenges are held. After they are resolved, the court issues a final decree which defines the rights of every water right owner within the stream system or groundwater basin.

CONCLUSION

The District's historical and legal research has turned up the following points:

On June 15, 1918, the Elephant Butte Water Users Association entered into an agreement with the United States and the Elephant Butte Irrigation District where the Water Users Association dissolved and the irrigation district assumed the liability for distribution and drainage works. In addition, the District received an assignment of all of the association's assets and rights.

The United States agreed to release the individual shareholders and the lands of the shareholders of the association from liens on their property as security for the repayment of the construction obligation once the District assumed the obligation for repayment of the construction of the Rio Grande Project.

Congress contemplated under the Reclamation Act, that when the District completed repayment of its allocated construction costs for the Project in 1973 the United States should no longer be the record holder of the Project water rights. Their rights in the water rights were extinguished with payout.

The priority dates for the Project water supply relate back to the dates in filings by the United States in 1906 and 1908. The River Alluvium which underlies the Rio Grande and which forms the supply for many shallow wells located within the District is part of the Project supply. The full irrigation of the Project lands within this region was the intent and purpose of the appropriations.

Throughout the history of the Project, there has been an increasing use of groundwater to supplement the supply of surface water available from the Rio Grande. This use of groundwater commenced at least as early as 1940s and probably earlier. In the early and mid-1950s, the Rio Grande Project in New Mexico suffered water shortages because of a series of droughts in the watershed of the upper Rio Grande in Colorado and New Mexico and because of the up-stream use of water in excess of Rio Grande Compact entitlements. This severely impaired the ability of the members of the irrigation district to continue to grow crops with surface water, and led to increased groundwater pumping in the early and mid-1950s. Most of these wells have been drilled into the shallow aquifer which constitutes the Rio Grande alluvium, and others have been drilled into the underlying aquifer known as the Santa Fe Formation. These wells have been used, replaced, and supplemented by additional wells for the same purposes over the years.

The surface water delivery within the District contributes tremendously to the recharge of the River Alluvium and Santa Fe Formation in the Lower Rio Grande.

Each owner of water-righted land of the District is entitled to water the acreage listed in their contract based on available Project water supply.

State statutes provide for the equitable distribution of Project water to all of its water users and generally govern how the District operates and manages the water it distributes to its water users.

The District will defend the right of its water users to have delivered and use all of the Project water supply that the 90,640 acres of water-righted land within the District is entitled to use. Additionally, the District will defend any and all attempts by federal or state agencies to obtain or use the District's share of Project water for purposes that do not benefit its water users.

Given the dynamic institutional context within which water allocation issues are currently determined, it would appear that maintenance of the status quo with respect to allocation of water by the District is unlikely. The District is a management entity whose current policy has been directed solely toward agriculture. However, in looking to the future, it appears to be appropriate to consider the District as a water management entity which must address water management within broader parameters than those currently perceived to be relevant. The District's management goals will involve future deliveries of water to residential, commercial, and industrial uses as well as the traditional agricultural uses.

The District's water management activities and ongoing planning in anticipation of a more diverse constituency's future needs will be essential if the District is to maintain the perception that it is and will continue to be an appropriate trustee of this critical resource.

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EFFECTIVENESS OF CONSERVATION POLICIES ON NEW MEXICO RESIDENTIAL WATER DEMAND[62]

Douglas Gegax, Tom McGuckin, and Ari Michelsen[63]

ABSTRACT

The factors that determine single-family residential water demand in the southwestern United States are investigated with emphasis on New Mexico consumer responses to changes in price levels, rate structures and implementation of other residential water conservation programs. Residential water demand determinants and conservation program effectiveness for consumers in seven cities were evaluated over an 11-year period using a new time series, cross-sectional regional database and regional water demand model developed for this study. Results indicate that residential consumers across the southwest region of the U.S. are very unresponsive to price increases under current rate structures, requiring large increases in price to achieve small reductions in demand. However, individual city consumer price responsiveness varied substantially depending on specific city prices and other conditions. Although consumers in New Mexico cities were found to be more responsive to increases in price than the regional average, their demand for water was still very price inelastic. Across the region, nonprice conservation programs were found to be effective, but only

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[63] Authors are listed in alphabetic order, senior authorship is not assigned. Douglas Gegax and Tom McGuckin are associate professors, Economics Department, New Mexico State University and Ari Michelsen is assistant professor, Economics Department, Washington State University. Information contact: Tom McGuckin; phone 505 521-7352; e-mail mudduck@ibm.net.

when a substantial number of programs were conducted over longer periods of time. Small changes in water rates or implementation of haphazard conservation programs will most likely not produce discernable result.

INTRODUCTION

Most western cities and municipal water departments have adopted water conservation programs designed to reduce per capita use of water. The rational for these programs vary but the major argument is that water is a limited resource subject to increasing supply costs and demands. Conservation policies address the standard microeconomics question of how to allocate a scarce resource. One economic solution is to set water prices equivalent to what would be determined by competitive market forces; that is, water prices should reflect the added cost of additional water supplies. The consumer then would adjust to the most beneficial water use level.[64] For various reasons, including uncertainty about consumer response to price increases and the desire or need to remain revenue neutral, water departments are reluctant to employ price as the sole method to achieve conservation[65] (Martin and Kulakowski 1991; Bonbright et al., 1988). Revenue neutral conservation oriented rate structures and nonprice conservation programs (e.g. public information, retrofit device distribution or ordinances) are policy approaches that can be used independently or in conjunction with changes in price to reduce water use (Howe 1982; Maddaus 1987). The unanswered question for utilities considering water conservation is what program or combination of programs is most effective.

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[64] Water use that would result in maximum net benefit and efficient levels of conservation. Several western states have adopted laws stating that water use should be subject to public welfare and conservation criteria stemming from a U.S. Supreme Court Decision, "Sporhase et al. vs. Nebraska ex re. Douglas", July 2, 1982.

[65] The relationship between the use of water and the price of water is referred to as the demand for water. The "law of demand" suggests that this is an inverse relationship. If demand is relatively unresponsive to increases in price, water department revenue will increase more than the reduction in water use resulting in excess profit.

Very little empirical information exists for an individual city to determine the effectiveness of price, rate structure or nonprice conservation programs. Because of this, estimates of consumer response at one location are often extrapolated and assumed to apply to consumers in a different location. The economic and political consequences of ineffective programs or errors arising from these transferred policies can be substantial. It is important for water departments and policy makers to have reliable information on the determinants of water demand and the applicability and effectiveness of various conservation policies.

The factors that determine single-family residential water demand are investigated in this paper, with emphasis on regional and New Mexico consumer responses to changes in price levels, rate structures and implementation of other residential water conservation programs. A regional residential water demand model was constructed to examine the effects on demand from changes in prices, nonprice conservation programs, climate, drought, socioeconomic conditions and water use over time. Parameters in the model were estimated using a time series, cross-sectional database of residential water demand conditions in seven cities in three southwestern states (California, Colorado and New Mexico). This extensive database of monthly observations spans over an 11-year period and was developed specifically for use in this study (Michelsen et al., 1998). In this paper, we address the determinants and effectiveness of price and other conservation policies in reducing per capita water use in the southwest United States.

PRICE AND NON PRICE CONSERVATION

Evaluating policies that attempt to change residential water use requires a model of consumer choice, that is, a model of water demand. In general, the quantity of water demanded by residential consumers is assumed to be influenced by the price of water, climate conditions, household income, number of people per household, number and efficiency of water using appliances and other factors (Young 1973; Danielson 1979; Foster and Beattie 1979; Howe 1982; Billings and Day 1989; Nieswiadomy 1992). Demand models empirically quantify the relationship between these factors and water usage. Our analysis concentrates on the factors that are controllable decisions of a water utility in order to induce a desired level of water conservation.

For our purposes the demand model is defined to include two types of variables: "utility variables" that are controlled by the water utility, and "environmental variables" that influence water demand but are external to the utility decisions. Utility variables of water demand (*WQ*) include the price of water (*P*), rate structure (*Rate*), and the number and type of non-price water conservation programs (*CONS*). Environmental variables of water demand include climate conditions such as temperature (*Temp*) and precipitation (*Prec*) and socio-economic characteristics such as household income (*Inc*) and city size (*ACCT*). Other environment related variables considered are time (*Time*) and severe drought periods (*DRGT*).

The generalized model of water demand used in this analysis is specified as:

$$WQ = f\,(P, Rate, CONS; Temp, Prec, Inc, ACCT, DRGT, Time) \qquad (1)$$

where the quantity of water demanded by residential consumers in a city is a function (*f*) of utility and environmental variables. Although equation (1) is empirically estimated using both sets of variables, the utility variables are of primary interest.

Utilities may be able to achieve water conservation objectives through economic incentives or other nonprice conservation programs. Increasing price is a direct economic incentive for consumers to reduce the quantity of water used. Nonprice conservation programs may also affect consumers demand for water. Instead of using an increase in price to achieve a reduction in the quantity consumed, nonprice programs such as education may influence consumer preferences so consumers demand less at the same prices. Figure 1 is a representation of residential water demand and shows, in theory, how either price or non-price conservation programs or a combination of programs may be used to achieve reductions in water use. Starting with demand curve 1, a conservation price program is represented by increasing the price per unit of water from P1 to P2. Here, consumers reduce their consumption from W1 to W2. A similar reduction in use may also be achieved through non-price programs that influence consumer preferences and shift the demand curve to the left, from demand curve 1 to demand curve 2. If this shift is considered at price level 2 (i.e., considered in combination with the price program), consumption will be further reduced from W2 to W3. The less responsive consumers are to price (the steeper the demand curve), the greater

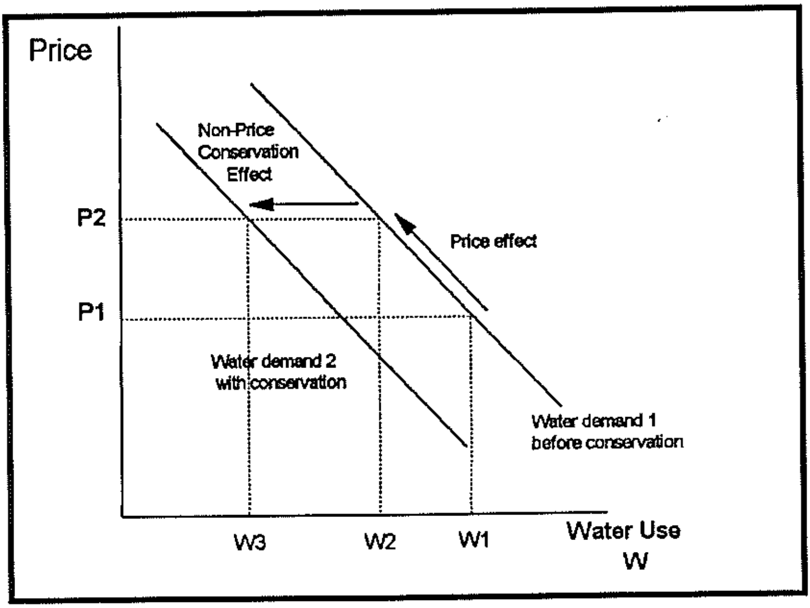

Figure 1. Water Price and Non-Price Conservation Effects

the increase necessary to achieve a reduction in use. Before any conservation program is implemented, it is critical to know how responsive consumers will be to that individual program and to the combination of programs. One of the primary objectives of this research is to estimate and evaluate consumer responsiveness to price and nonprice programs in the southwest region.

Price and Rate Structure

It is rare that a consumer actually sees a simple unit price for water, say $2.00 per 1,000 gallons. Most utilities employ a rate structure that involves multiple prices and/or a combination of fixed service charges and per unit water prices. Fixed service charges, an amount paid regardless of the quantity of water consumed, provide a stable source of revenue to the utility that is insensitive to the quantity of water used. In addition to a fixed service charge, four general types of per unit rate structures are predominantly employed by municipal water utilities. These are:

(1) a uniform rate structure (the same rate/price for each unit consumed);
(2) declining-block rate structure (a higher price is applied to an initial block of water consumed while a lower price is applied to water consumed over and above a specified amount);
(3) inclining-block rate structure (a lower price is applied to an initial block of water consumed while a higher price is applied to water consumed over and above a specified amount); and,
(4) seasonal rates (differential rates based on seasons).

Inclining and declining rate structures are called tiered or block rate structures because different prices apply to different quantities (tiers) of water consumed. A combination of water department objectives, such as revenue stability, revenue neutrality and conservation, are involved in the selection of a particular rate structure. Our focus is on conservation incentives of rate structures.

Theoretically, declining-block rate structures encourage higher water use because the average price paid for water decreases as water usage increases. Absent significant fixed service charges, inclining-block rate structures are, in theory, conservation oriented because the price paid for water increases as water use increases. Under a uniform rate the price of water is the same whether it is the first or last unit consumed. A uniform rate is contrasted to an inclining rate structure in Figure 2. The horizontal axis represents the number of units of water (quantity) consumed per month, and the vertical axis represents the price per unit of water. An example of a uniform rate structure is represented by the horizontal dotted line where all units of water are priced at $1.50 per 1,000 gallons. The inclining block rate structure – represented in Figure 2 by the solid step--involves two prices for water: $1.00 per 1,000 gallons for the first 10,000 gallons of consumption and a higher second rate of $2.00 per 1,000 gallons applied to consumption over and above 10,000 gallons per month. For

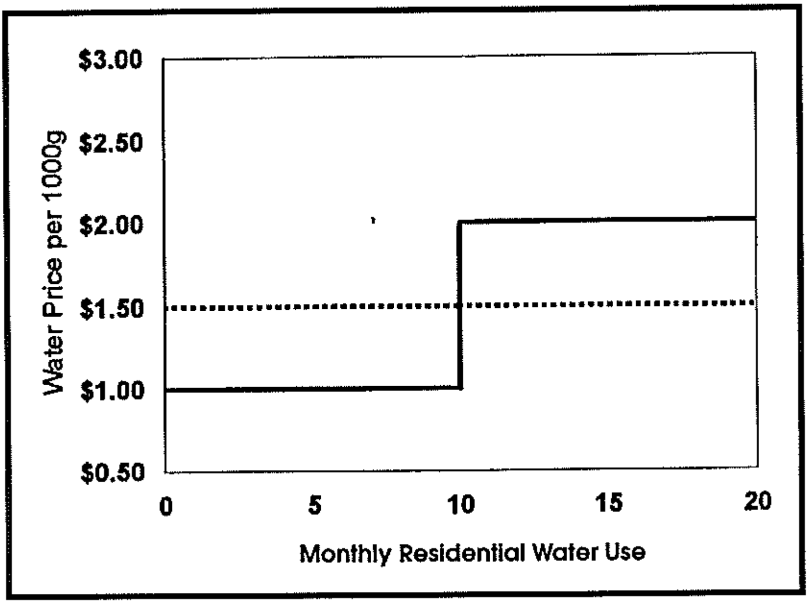

Figure 2. Example of Uniform vs. Increasing Rate Structure

perspective, monthly water use in the region averages 11,000 gallons per month per household and ranges from 4,000 to 29,000 gallons depending on the season, location and year.

Figure 3 superimposes the concepts of different household demand curves and two types of rate structures, uniform and increasing block rates. Three individual or representative household demand curves are illustrated; average, high and low (for a given season, the differences between these residential demand curves would be due to socioeconomic factors). For a typical or average household facing a uniform rate of $1.50 per thousand gallons, Figure 3 shows water demand would be 10,000 gallons. High and low users would have a variation of 5,000 gallons per month above and below the average respectively. Now consider the revenue neutral inclining rate structure shown in Figure 3. The inclining rate structure does not change the consumption of the average user (the uniform and inclining rate

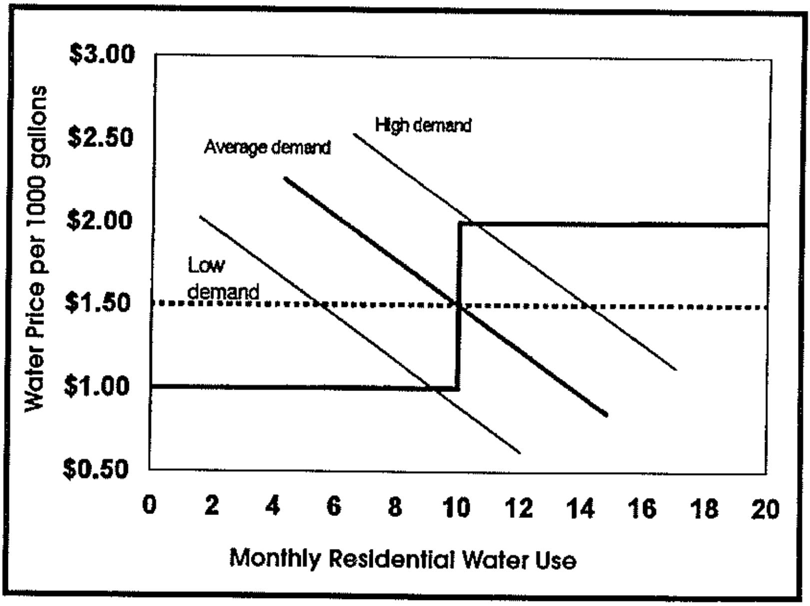

Figure 3. Impact on Different Users Increasing Block Rate Structure

structure prices intersect the demand curve at the same point). However, the inclining rate structure does have an effect on both high and low users. Water use of both these consumers is moved toward the average.

Even though a change in rate structure, say from uniform to inclining block, may be revenue neutral, its does not necessarily follow that there is no overall effect on water use. In fact, tiered structures greatly complicate estimation and prediction of price effects.

Marginal Price and Average Price

One method used to represent differences in rate structures is to compare average and marginal prices. Marginal price (MP) is defined as the price of the next unit of water consumed. In neo-classical microeconomic theory, consumers make their decisions or respond to the marginal price. In Figure 3, the marginal price under the uniform rate structure is a $1.50 per thousand gallons. In a tiered block rate structure, marginal price is the price per unit associated with the quantity consumed. For example, under the tiered structure in Figure 3, the marginal price faced by the low user is $1.00 while the high user faces a marginal price of $2.00.

A customer's average price (AP) is calculated by dividing the total customer's cost of water consumed, the total customer's bill, by the total number of units used (AP = total bill ÷ total quantity consumed). Under a uniform rate structure, and absent any fixed service charges, the marginal price is constant and equal to the average price.[66] For a use level of 14,000 gallons and the inclining rate structure shown in figures 2 and 3, the total cost of a monthly bill would be $23.00 ($1.50 x 10 units + $2.00 x 4 units) and the average price would be $1.64 per thousand gallons. Note that the average price is below the marginal

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[66] Under a uniform rate structure that includes a fixed service charge, the average price will always be decreasing as the quantity of water consumed increases.

price of $2.00 and, thus, the average price is increasing in usage. Absent significant fixed service charges, customers who consume on the second block of an inclining-block rate structure will always face a marginal price which exceeds the average price.

Almost all water departments have a fixed service charge. This fixed charge further complicates consumers' perception of the "price" of water. Depending on the relative size of the fixed charge and the per unit price for water, the average price per additional unit of water consumed may be declining or increasing. Under revenue neutral conditions, a substantial fixed charge means that the total of the per unit charges must be reduced, sometimes leading to a situation where the marginal price is less than the average price and average price continues to decline with increased consumption. Although total cost will still be increasing with this common multi-part type of rate structure,[67] a declining per unit price for additional consumption would be expected to provide little encouragement for conservation.

Price Variables for Alternative Rate Structures

Under multiple-part rate structures there is typically a divergence between the average and the marginal price and it is not apparent which price(s) consumers perceive and respond to. The problem of what price consumers respond to is an empirical issue that must be addressed when modeling demand and evaluating conservation programs. The approach applied here is a modeling technique developed by Shin (1985) which tests whether consumers respond to average price, marginal price, or a combination of the two. The basic concept underlying the Shin model is that, while in theory consumers respond to the marginal price, it is difficult for consumers to determine the actual marginal price from a typical utility bill. If the benefits of learning the true nature of the rate schedule are less

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[67] Even with an increasing tiered rate structure (increasing marginal prices) average prices may still decline with large fixed charges or when the marginal price remains less than the average price.

than the costs, it is likely that the consumer will react to some proxy of marginal price, such as an ex post calculated average price from a recent bill. If the costs of learning the true nature of the rate schedule are low, it may be that the consumer reacts to the true marginal price. In order to incorporate a number of possible price response situations, the price variable in the demand model is redefined as the perceived price (P^*), the price perceived (and responded to) by the consumer. P^* is a set of variables in the demand model incorporating both the actual marginal price and the ratio of average to marginal price. Statistical tests of the demand model perceived price results are applied to indicate whether consumers are responding to marginal price, average price or some combination of the two.

Effects of Non-price Conservation Programs

The effects of non-price conservation programs employed by water utilities within and across regions has been analyzed little beyond the inclusion of dummy variables within regression analyses.[68] Studies that have explored the effects of non-price conservation programs on single-family residential water demand typically examine a single program by comparing water demand before and after a program without adjustment for other demand factors and trends or are engineering estimates of expected device reductions (e.g., distribution of shower nozzle retrofit devices) without follow up confirmation of consumer compliance or subsequent removal of devices. Representation of these programs in water demand models has been restricted to binary variables simply because data necessary for a more detailed examination is seldom documented or available for analysis (Moncur 1987; Nieswiadomy 1992). Moreover, these studies do not distinguish between the different types, or number, of non-price conservation programs.

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[68] In these studies the dummy equals zero if no non-price programs are in effect, otherwise the dummy equals one. Therefore, a utility with one program is characterized the same as a utility with ten different programs.

Nieswiadomy (1992) analyzes how the presence or absence of any conservation program influences household use levels. His analysis uses 1984 annual AWWA survey data from U.S. water utilities serving populations greater than 10,000. A dummy variable representing whether or not any conservation program was in place and another dummy for the existence of any public information programs were included in three forms of double-log estimation equations for four regions of the United States. In Nieswiadomy's study, public education programs were statistically significant in influencing water demand in the western region of the United States under the average price model and the price perception model. On the other hand, overall conservation programs were statistically insignificant under each of the three models in all regions of the United States. Of particular interest are the effects of multiple conservation programs and the separate and combined effects of price and non-price conservation programs on residential water demand in the southwestern U.S.

Although specific water pricing data is documented by water utilities, information about non-price conservation programs is often not recorded in any detail or degree of consistency. As part of this analysis, extensive efforts were made to collect and compile specific and consistent information on all non-price conservation programs implemented in each of the study areas on a monthly basis over a 15-year period. But the qualitative nature of non-price programs and the lack of uniform records by utilities prevents detailed analysis of individual programs.

As a proxy variable for non-price program efforts by utilities, a continuous non-price conservation variable (CONS) was constructed to represent the breadth of conservation programs in effect on a monthly basis. This method provides a measure of the number of individual programs employed in a particular city on a monthly basis throughout the time period of the study, allowing the distinction between study areas with numerous programs and areas with only a few, or none at all. Although this methodology assumes that all programs and all levels of commitment per program are identical, there was insufficient data to identify and separate individual program levels of effort.

Environmental Climate and Socioeconomic Variables

Residential water demand for outside uses are assumed to be influenced by climate conditions. Nieswiadomy (1992) indicates that average rainfall negatively impacts annual water use in the southern region of the United States and average temperature significantly impacts annual water use (positively) in the north central, south and western regions of the United States. Climate effects are incorporated in the regional water demand model in this study with variables for observed monthly precipitation (*Prec*) and average monthly temperature (*Temp*) for each city. Median per capita incomè (*Inc*) is used as the income variable in the water demand model (Foster and Beattie, 1979).

During the late 1980s to early 1990s, California experienced a significant drought that required water use to be curtailed in many urban systems. The severity of the drought was well publicized. Many California water utilities implemented additional water conservation programs – some mandating reduction in use by residential consumers. To distinguish the response to the California drought situation from other conservation efforts, we define a binary variable for the drought period in southern California during the early 1990s (*DRGT*). In addition there may be trends or systematic changes in consumer tastes that are independent of conservation programs. We use a continuous time variable (*Time*) to capture consumer trends toward water use independent of other factors included in the model.

Finally, the water demand model is applied to citywide data requiring a proxy variable for city size. Here we use the number of single family residential accounts (*ACCT*) each month for each city. All monetary values are in 1995 constant dollars.

Regional Water Demand Data

The variable relationships in the regional water demand model were empirically estimated using monthly observations from seven cities in three states over an 11-year period, 1984 through mid-1995 (Michelsen et al., 1998). The seven cities are: Los Angeles and San Diego, California; Broomfield and Denver, Colorado; and Santa Fe, Albuquerque and Las Cruces, New Mexico. One of the difficulties encountered when using a single city to estimate water demand determinants is a lack of variation in price and other factors, restricting the results and application to other situations to a very narrow range. The cities selected for this study provide a broad range of water prices and rate structures, non-price conservation program efforts, socio-economic and climatic variables. A good example of the increased variation in price obtained by investigating more than one city can be found in New Mexico, where the marginal price of water in 1995 for consumption between five and ten thousand gallons per month ranges from $0.63 per thousand gallons in Las Cruces to $3.50 per thousand gallons in Santa Fe. This is also the widest range in marginal price across the region.

In all but one of the seven cities, the water departments' have changed their rate structure one or more times over the period of study, from uniform or declining rates to inclining and/or uniform plus seasonal rates. As an indication of the variability and complexity in rate structures across the region, over a 15-year period from January 1980 through April 1995, there were 43 different residential account price levels in effect in Los Angeles. By 1995 in New Mexico, Albuquerque's rate structure consisted of a fixed service charge and consumption based uniform rate with a seasonal surcharge depending on the total quantity consumed and both Santa Fe and Las Cruces had rate structures with a fixed service charge and inclining tiered rate structures depending on the quantity of water consumed per billing period.

Five of the seven cities in this study had employed one or more major non-price conservation programs during the period of study. Across the region, San Diego had implemented the largest number of non-price conservation programs (16) with at least six major programs in effect during the entire 11-year study period. Denver and Los Angeles had implemented from three to 13 programs over the study period. In New Mexico, Santa Fe had implemented from one to four major programs beginning in the late 1980s. Albuquerque started with six non-price conservation programs in 1994 and Las Cruces had no major non-price conservation programs in effect during the study period.

There was wide variation across the region in the quantity of water consumed per single family residential household. Both the low and high average annual monthly water use were in New Mexico, with consumption ranging from seven thousand gallons in Santa Fe to over fifteen thousand gallons in Las Cruces (average over the period from April 1993 and April 1995). In New Mexico, winter (low) and summer (high) seasonal average consumption per residential account in thousands of gallons per month was, respectively: Albuquerque, 7.95 and 24.03; Las Cruces, 8.37 and 23.46; and Santa Fe, 5.26 and 10.01. Consumers' response to price and non-price conservation programs varies by season and with the quantity used.

The annual average monthly bill (April 1993 and April 1995) per residential account in the region ranged from $14.44 in Denver to $30.71 in San Diego. In New Mexico the annual average monthly bill was $16.64 in Albuquerque, $17.49 in Las Cruces and $29.82 in Santa Fe.

The number of cities and variation in characteristics, period of time covered and inclusion of price and multiple non-price programs make this one of the most comprehensive data sets used for analyzing residential water use and the effectiveness of conservation programs.

WATER DEMAND MODEL RESULTS AND ANALYSIS

This section presents empirical results of the regional residential water demand model and analysis of consumer price response and price perception. In addition, the model results of the effectiveness of non-price conservation programs (independent of time, drought and other effects) are investigated. Residential water demand for the region is estimated using a time-series, cross-sectional (TSCS) database wherein the variable coefficients (relationships) are restricted to be the same across all seven cities. That is, the regional model uses the observations from all seven cities to estimate regional water demand variable relationships. An important outcome of this approach is that the findings can then be extended to other southwestern cities.

The regional water demand model was estimated using maximum likelihood regression techniques that correct for autocorrelation and groupwise heteroscedasticity. The regression techniques are fully described in Green, Chapter 16 (1993). Statistical estimation was conducted using LIMDEP^{tm} version 7.0.

Empirical results indicate that the regional water demand model is an excellent fit and was able to account for 96 percent of the variation in water demand.[69] Almost all of the regional water demand model variables were statistically significant at a 99 percent level of confidence and showed the expected relationships to water demand. Both price variables (*P**), temperature (*Temp*), time (*Time*), income (*Inc*), number of accounts (*ACCT*) and conservation program (*CONS*) variables were statistically significant determinants of water demand. Two variables, precipitation and drought effects, independent of climate conditions and conservation program efforts were found not to be statistically significant.

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[69] Maximum likelihood techniques do not yield the familiar correlation coefficient (R^2) as a measure of statistical model fit. Water demand forecast results of the regional model were regressed against actual water demand observations to provide an indication of model fit.

Consumer Price Perception

The perceived price estimated coefficients, both marginal price and the ratio of average to marginal price, have the expected negative sign, consistent with the law of demand and indicating that as price increases the quantity of water demanded (consumed) decreases. Using the Shin price perception test, we evaluated whether consumers are responding to marginal prices, average prices or a combination of the two. The regional model results suggest that consumers do not respond solely to marginal price or average price, rather they respond to some combination of the two.

Price Conservation Response

Residential water demand across the region was found to be very price inelastic, that is, consumers were very unresponsive to changes in price. The estimated regional price elasticity of -0.04 indicates that for a one percent increase in price, water use on average would only decrease by four hundredths of one percent for the region as a whole.[70] However, the model also shows that individual city consumer price responsiveness varies substantially and depends on the specific prices and conditions that exist for that city. For example, using the regional model results with the specific conditions that exist in Albuquerque and Las Cruces, New Mexico, demand is estimated to be more price elastic than the region overall, with price elasticities of -0.11 and -0.38, respectively (still quite inelastic).

The general finding of inelastic regional demand and location specific variation in price elasticity have important implications for utility managers and policy makers involved in evaluating price and rate designs and forecasting individual city and regional water

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[70] The use of the perceived price variable – a function of both MP and AP – requires a more elaborate calculation of elasticity. Though the demand function is a "constant" elasticity function with a traditional concept of price, the function does not have constant elasticity with respect to both MP and AP.

demand. In particular, substantial errors are likely to arise if a general price elasticity estimate for the region or from another city is used to design a rate structure and set prices for another location.

Non-Price Conservation Effects

Non-price conservation programs across the region were found to have a significant, negative influence on water use. The non-price conservation parameter (*CONS*) is a measure of the number of programs that are in effect at that particular point in time. Based on the results of the regional water demand model, residential water use was reduced <u>on average</u> by 2.9 percent per non-price conservation program. Because the information regarding non-price programs is incomplete, the model and this parameter were not able to distinguish individual types or specific programs nor the residual or lasting effects of non-price programs.

It is important to note that this average effect per conservation program may not represent the marginal effect of an additional program for a city that has had very few conservation programs or, on the other hand, a city that has numerous programs. This regional estimate is driven by the aggressive conservation efforts of several cities. However, results from additional analysis have indicated that conservation responsiveness in individual cities with few if any programs is lower, and in some cases even zero. Furthermore, the 2.9 percent average per program probably overstates the total conservation effect of the last program implemented for cities such as Los Angeles and San Diego where numerous programs were already in effect prior to the beginning of the time period covered by this study.

Price vs. Non-Price Conservation Effectiveness

The individual and combined effectiveness of price and non-price programs are illustrated in Figure 4 which represents the experiences of Los Angeles. From 1984 to 1994, the Los Angeles Department of

Water and Power effectively doubled marginal residential water prices from $1.28 to $2.44 (measured in constant 1995 dollars) and implemented eight additional non-price conservation programs. During this time, average use per household decreased from 20.15 to 16.08 thousand gallons per month. The water demand curves shown in Figure 4 were estimated from the regional water demand model and indicate that approximately half of the decrease in quantity consumed was due to price increases (movement upward along the original demand curve to a higher price) and the other half was due to an increase in the number of non-price conservation programs (shift of the demand curve to the left).

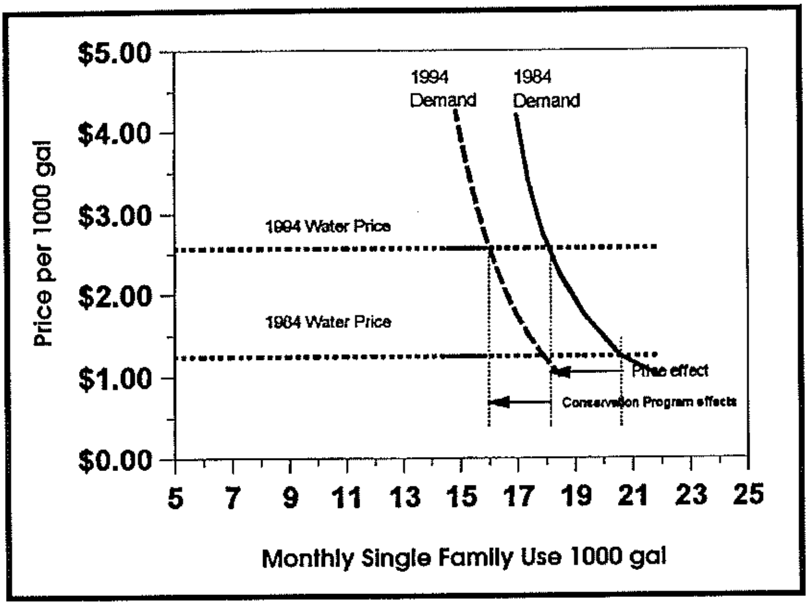

Figure 4. Residential Demand for Water, Los Angeles, Calif. 1984-1994

Figure 5 illustrates the demand curve and hypothetical effect on water consumption from a doubling of marginal price for two New Mexico cities, Albuquerque and Las Cruces. The substantial increase in the

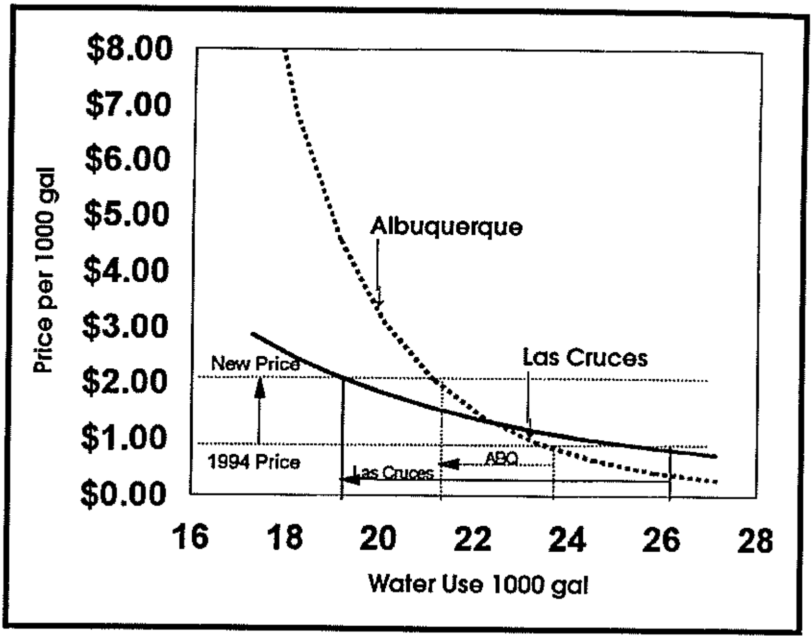

Figure 5. Relative Demand Response to Price, Albuquerque vs. Las Cruces, NM

marginal price of water is estimated to result in reduced demand in both cities, but the responsiveness differs depending on the local conditions. In Albuquerque, a doubling of the marginal price (100% increase) is estimated to result in an 11% reduction in the quantity demanded. Consumers in Las Cruces are estimated to be more responsive, where doubling of the marginal price is estimated to result in a 38% reduction in the quantity demanded. The difference in response elasticity can be attributed to several significant differences in the conditions of these two cities, especially the initial level of marginal price. The initial marginal price of water in Albuquerque in 1995 was almost fifty percent higher than the marginal price of water in Las Cruces. At low prices, consumers in Las Cruces are on the relatively flat (responsive or elastic) portion of their demand curve. Both economic theory and the empirical model results suggest that consumers would become less responsive with further price increases.

CONCLUSIONS AND IMPLICATIONS FOR FUTURE RESEARCH

A regional model of residential water demand was developed and estimated with time-series, cross-sectional data to evaluate empirically the effects of price, rate structures and non-price conservation programs on residential water consumption, adjusted for other conditions that may influence water use. Statistically, the regional water demand model was an excellent fit. The estimated relationships of the model variables explained almost all of the observed variation in water demand for the seven cities in the region. Water price was found to have a significant and negative impact on water use and water demand for the regions was found to be very price inelastic, more so than has been suggested in other studies. However, the price elasticity for individual cities in the region varies substantially from the overall regional estimate. The price elasticity for an individual city depends on the specific price, rate structure and other conditions in that city. The consumers in Albuquerque and Las Cruces were estimated to be somewhat more responsive to price than the regional average response, but demand in these cities was still very price inelastic requiring large increases in price to achieve relatively small reductions in water use.

The concept of a "price" per unit of water of water is more complex under multi-part rate structures with fixed service charges and tiered block rates. Under these conditions more than one price exists that consumers may respond to and, depending on the rate structure, that price may or may not provide incentive to conserve. Fixed service charges are used almost universally by water departments and with fixed charges uniform or inclining block rate structures intended to encourage conservation instead frequently result in declining average prices as consumption increases, even when marginal prices are rising.

Statistical tests to determine whether consumers perceive and respond to marginal prices or average prices were inconclusive. Regionally, consumers appear to be responding to some combination of marginal and average prices. This makes it more difficult for water departments to design effective conservation rate structures for specific cities because the price or prices consumers respond to is not clear. These results indicate that utilities interested in using price to encourage conservation should carefully examine the combined incentives provided by their rate structures.

Non-price conservation programs appear to be effective if the water utility achieves a critical mass of programs. For cities with a small number of programs or relatively new experience with conservation programs, the non-price programs had no effect on demand. Because the information regarding non-price programs is incomplete, the analysis does not distinguish the effectiveness of individual types or specific programs nor the residual or lasting effects of non-price programs. In summary, price and non-price conservation programs were found to be effective, but require a major commitment by water departments. Small changes in water rates or implementation of haphazard conservation programs will most likely not produce discernable results.

A regional model may *not* be appropriate for urban water demand estimation in all cities throughout the southwestern United States. By restricting the variable coefficient estimates to be the same across all cities, the implicit assumption is that residential water users have similar responses between cities (this does not mean that water use is constant over cities, as many other factors such as rate structures, climate, income and conservation programs also influence water use levels). If this assumption is inappropriate – to be determined through future research – then a more specific formulation of the demand model should be used which allows for changes in variable relationships over time and/or between cities.

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ECONOMICS OF WATER CONSERVATION

Frank A. Ward[70]

SUMMARY

This paper examines how economic principles can be used to establish plans that foster water conservation. Economically effective water conservation is promoted by policies that confront all water users with the real cost of their actions. The 'use it or lose it' principle of the prior appropriation doctrine is an important institutional barrier to water conservation. Legislative enactments that define short-term water trading to be a beneficial use of water is one institution that promotes conservation by spreading existing water supplies to higher total beneficial use. By informing existing water rights owners of the real cost of their water use, such legislation creates a market, promotes wider beneficial use and produces more total economic benefit from available water in dry regions.

THE PROBLEM

Water scarcity and the need to develop better institutional flexibility to mitigate that scarcity are the most compelling limits on the economic development and continued welfare of the people who live in the interior western United States. Water economics offers insights into designing institutional flexibility that reduces the costs of confronting and adapting to water scarcity.

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[70] Professor, Department of Agricultural Economics and Agricultural Business, New Mexico State University, Las Cruces, NM 88003, email: fward@nmsu.edu
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In attempting to reduce the cost of water scarcity, water managers and policymakers have three related goals. First, they aim to understand how hydrologic and economic forces, social institutions, and water management decisions affect the distribution of water-use opportunities over time and place. Next, they try to set up objective criteria that can be used to evaluate the consequences of management decisions on the total benefits to the water-using public. Third, they design water management institutions that increase total benefits from available water and adapt those institutions to changes in water supply, water demand, and social values. To simplify, the aim of water management and water policy is to formulate flexible institutions that allocate scarce water over time and place to produce the highest benefits to current and future generations.

Economics helps to think about ways to spread scarce water and related resources to produce more total benefit to people. Several reviews of the water economics literature have been written, including Eckstein (1958), Wollman (1959), Young et al., (1972), Bower, et al. (1984), Young (1996a,b) and Gibbons (1986) just to name a few. As described by Young and Haveman (1986), benefit-cost analysis (BCA) is the main analytical framework for evaluating the economic effects of water management decisions. This paper's aim is to illustrate how economic principles can provide important insights into establishing plans that promote effective water conservation.

WATER CONSERVATION

Significant growth in water demands in conjunction with economic and population growth stress limited water supplies and water management institutions in arid regions. In dry places like New Mexico the notion of establishing effective policies to promote more water conservation means little unless it is based on economics. With this in mind, a definition for economically effective water conservation is any public or private decision that promotes a change in water use over time that pays for itself in human benefits gained.

One way to promote economically effective water conservation is to establish institutions that confront all water users with the real cost of their actions imposed on other people. An individual water user implements only those decisions that change water use over time for which his own benefits exceed his costs. However when a water user faces the real cost of his action (benefits lost from other uses displaced), he implements only those decisions that change water use over time for which society's total benefits exceed its total social costs. For purposes of this paper, society's total benefits exceeding its total costs is what is meant by paying for itself in human benefits gained.

Although this concept of water conservation is fairly straightforward, a major difficulty in implementing it as practical water policy lies in measuring social benefits and social costs. Information on these benefits and costs is usually scarce, but is nevertheless required for policymakers to design good institutions for conserving water. This paper examines the institution of temporary market transfers of water from agriculture to cities.

WATER DEMAND PATTERNS: CITIES V. AGRICULTURE

In the dry western U.S., cities have very different patterns of water use than agriculture. Much of this difference can be attributed to the effects of price changes on water use. This difference is illustrated by the concept of price elasticity.

The price elasticity of demand for water measures the percent change in water use from a given percentage change in its price. High-valued necessities like drinking water, typically have low price elasticities while lower-valued more water-intensive uses such as irrigated agriculture, have higher elasticities. A high price elasticity of demand for water means that a small percentage change in its price causes a large percentage change in quantity used.

Agriculture

Water demands for irrigated agriculture are characterized by high price elasticities compared to cities in most parts of the world. Depending on the crop, soil, climate, weather, and period of adjustment, many studies have shown that price elasticities for irrigated agriculture range from -1.0 to -3.0. A small percentage change in the price of water causes major impacts on water used in and incomes derived from agriculture. Young (1996a) summarizes a study by Herrington (1987) that reviews a number of earlier modeling studies on irrigation demand elasticity which show demand elasticities in agriculture to be relatively high, especially at higher water charges.

Irrigation water users typically respond to increases in water prices by making one of four kinds of adjustments:

(1) substituting between water and other inputs,
(2) changing the crop mix on irrigated land,
(3) reducing total irrigated area, and
(4) changing the pricing structure.

For all these adjustments taken together, the overall use of water in agriculture is considerably more responsive to price than for cities' use.

Cities

The price of water that a city is willing to pay is typically considerably more responsive to shortages than in agriculture. Based on the typical price of bottled water, people will pay more than $100,000 per acre-foot for drinking water. Even for normal household use, cities typically charge their customers more than $300 per acre-foot. What this means is that cities are usually willing to pay considerably more to assure needed supplies than is agriculture. Schneider and Whitlach (1991) present a comprehensive water demand study and extensively survey much of the previous literature. They showed that almost all estimates of long-run price elasticity of residential water demand in the U.S. falls between -0.3 and -0.7.

The relatively low demand elasticity for city water means that city demands in periods of shortage could provide a ready market for temporary use of agricultural water. Irrigated areas that are located close to cities can use the elasticity concept to advantage by recognizing that cities are willing to pay much more for water than farmers lose by taking it out of agriculture.[71]

ECONOMIC BENEFITS OF SHORT-TERM WATER TRANSFERS

Throughout most of the western U.S., agriculture owns most of the water and the associated senior water rights. In this region farmers and other water rights holders have an economic opportunity to increase profits in dry years by charging premium prices to cities and others who need wet[72] surface water.

Water transfers within agricultural regions have taken place for centuries. Maass and Anderson (1978) describe an effective water marketing arrangement that has been in effect in one area of Spain since the 15th century. Also, a considerable amount of water trading occurs among farmers throughout the western United States (Lund and Israel, 1995). The idea of trading water to promote greater economic activity with limited water supplies is old. The economic literature describing the benefits to all parties of voluntary water transfers is huge (e.g., Milliman 1959; Hartman and Seastone 1970; Howe et al., 1986).

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[71] A good example is Elephant Butte Irrigation District, New Mexico, 40 miles from El Paso, Texas.

[72] Another name for wet water is 'real water,' i.e., tradeable water transfer not derived at the expense of any other lawful water user. A few examples are: (1) net water savings resulting from not planting and irrigating a crop that would otherwise be irrigated; (2) stored water released that would not otherwise be released. The opposite of wet water is paper water, i.e., water proposed for transfer that does not create an increase in the water supply. An example is a proposal to market water when the seller is legally entitled to use under a water service contract or a water right that has not historically been used (California Department of Water Resources, 1993c).

INSTITUTIONAL BARRIERS TO VOLUNTARY WATER TRADING

Short-term transfers of water as a commodity,[73] through trading or leasing, offer considerable potential benefit to both a water right owner and a prospective water user. Despite the fact that ownership of the water right itself would not be affected, serious obstacles to such temporary transfers currently exist. Throughout much of the west many current water right owners are concerned that temporary transfers of water as a commodity, such as a one-year lease, may cause them to forfeit their right because of nonuse. The historic policy requires water rights owners to use their water or lose rights to its use (New Mexico First, 1997). "Use it or lose it" is an important principle of the prior appropriation doctrine that governs much western water policy, court decrees, and various rules governing water use decisions. In the 19th century when the west was being settled, use it or lose it was an important constraint to attach to a water right to ensure that water claims would be actually used, and not merely reserved for land speculation, while somebody else needed the water and could put it to beneficial use.

In mature economies, the concept of use it or lose creates a barrier to temporary transfers of water as a commodity. That barrier may limit wet water available for rapidly growing cities, or cities trying to cope with droughts. This fear of losing a water right is a serious obstacle to motivating a water right owner who may otherwise be willing to trade water on a short-term basis while still keeping the water right.[74]

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[73] Transfer of water as a commodity refers to trading the water itself for something of equal value without affecting the ownership of the water right.

[74] Another obstacle to transfers of water from agriculture to cities is a lack of adequate infrastructure to divert water. For example, Albuquerque New Mexico currently has no infrastructure to divert water from rivers, since it relies completely on groundwater (Daves, 1997).

Legislative bodies like the New Mexico State Legislature could remove this institutional barrier by enacting laws that declare short-term water transfers, in which water right ownership does not change, as a beneficial use of water.[75] By removing barriers to trade, such legislation could create a market condition by providing a profit incentive for water right owners to conserve water in exchange for cash.

AGRICULTURAL ADJUSTMENTS TO WATER SHORTAGES

Voluntary water transfers in which water is temporarily taken out of agriculture typically produce one or more of the following responses: fallowing (not irrigating) fields, farmers shifting to less water-using crops, substitution of groundwater for surface irrigation supplies, greater groundwater pumping, reduced water use, and releasing water from reservoir storage. Each of these responses by farmers who transfer water could produce cash for agriculture; by reducing usage in agriculture, greater water supply becomes available for other uses.

INSTITUTIONAL ADJUSTMENTS TO WATER SHORTAGES

Several kinds of water transfer arrangements have the potential to provide an economic opportunity for agriculture to reduce economic damages from drought (Lund and Israel, 1995). Examples are contingent transfers/dry-year options; spot market transfers; water banks; transfer of reclaimed, conserved, and surplus water, and water wheeling or water exchanges.

Contingent Transfers/Dry-Year Options

Prospective water buyers are sometimes less interested in acquiring permanent water rights than in increasing the predictability of their

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[75] Promoting water conservation and greater use of the state's waters was the motivation behind two identical bills sponsored in the 1998 New Mexico legislature to establish a state-sponsored water bank (H 452 and S 342). These bills failed, partly because they did not clarify how the proposed bank would affect a water bank already operating within the Middle Rio Grande Conservancy District.

water supply system during droughts. For both buyers and sellers, temporary transfers contingent on water shortages may produce a significant economic benefit. A city in need of wet water could pay the farmer a sum of money for the privilege of exercising the right to use water should an emergency situation arise. Then the city might also arrange to pay agriculture an extra sum if that right is actually exercised. Advantages for agriculture are the immediate acquisition of cash when the contract is established and added revenues if the contingent transfer option is carried out. The advantage to the city is access to wet water when most needed.

Spot Market Transfers

Spot market transfers are short-term transfers, typically agreed to and carried out within a short period like one year. These transfers typically set up a bidding process, often with some of the conditions for transfer, such as price or quantity of water, being fixed. Agriculture has the advantage of a spot market transfer by the immediate infusion of cash when the transfer takes place.

Water Banks

These are a special kind of a spot market organized and operated by a central banker, such as a state or federal government agency or possibly a group of water utilities. The bank is a mechanism for willing owners of a senior water right to lease water to the bank for release to renters on a short-term basis. The banker is responsible for organizing the lease and for keeping track of the supply and demand for money and water. A water bank is characterized by flexible, temporary transfers of water without changes of ownership. Bank participants may differ in each year.

The California Drought Emergency Water Banks of 1991 and 1992 are classic examples of institutions that coped with serious drought (California Department of Water Resources 1992, 1993a,b,c). Operated by the State of California, the bank acquired water in three ways:

by paying farmers for water they would have used to irrigate their fields resulting in unused water flowing past their farms; by purchasing surplus water from local irrigation districts; and by paying farmers or irrigation districts to use groundwater instead of surface water (Rich, 1994).

These banks taught water managers a number of important lessons (Dziegielewski, et al., 1993):

(1) water markets, even when severely constrained, still work;
(2) water has a high value for many buyers, and many senior water rights owners are willing sellers;
(3) very large amounts of water can be found if sufficient money is put on the table; and
(4) third-party interests in market transactions can be protected.

Water Wheeling and Exchanges

Electric power is often wheeled through the transmission system between power companies and generation plants to reduce the cost of power and to get it to where and when it's needed most. Water could be similarly wheeled through water conveyance and storage facilities to reduce economic damages from drought or rapidly growing cities.

Seasonal wheeling of water is common in agricultural regions in which different areas have complementary demands for water over time. For example, the City of El Paso, Texas needs wet surface water flows from the Rio Grande in the winter while the Elephant Butte Irrigation District (EBID) in southern New Mexico has limited need for its channel capacity in winter. So seasonal wheeling may provide opportunities for El Paso to exchange water with EBID during low-flow irrigation demand periods. Repayment could come in the form of added water and/or cash during the high-demand irrigation season.

If laws are passed that remove barriers to farmers renting water to cities, water not used in agriculture is available for cities, possibly at a lower cost than the cities' next cheapest source of water. The use of wheeling to meet environmental uses could involve the use of storage facilities to release water for instream flows when desired. Releases by the Middle Rio Grande Conservancy District (MRGCD) in central New Mexico from its upstream storage facility at El Vado Lake, paid for by environmental interests, provide an excellent example. Such releases could be implemented by the Albuquerque office of the Bureau of Reclamation and produce streamflows needed by the endangered silvery minnow in otherwise dry periods. Additional details on the operation of MRGCD are described elsewhere (Shah, 1997).

Transfer of Reclaimed, Conserved, and Surplus Water

Water purchases made available by reclamation or reduced water demands is a form of a water transfer. Recently the Metropolitan Water District (MWD) of California set up a 35-year contract to pay the Imperial Irrigation District (IID) several million dollars for canal lining and other system improvements in exchange for the water conserved. Israel and Lund (1995) report estimated savings at 100,000 acre-feet per year from IID's Colorado River water supplies. This similar potential for a mutually beneficial trade exists between cities and agriculture in other dry places like New Mexico and west Texas.

UNRESOLVED ISSUES

For water transfers to make a serious contribution to coping with drought by promoting water conservation, a number of policy questions must still be resolved.

- What is a good way to deal with the possibility that short-term water transfers such as banking may provide an incentive for new water use that would not otherwise take place?

If cities pay water rights holders to reduce their water use, some may start using as much water as possible to establish a higher baseline level of use.

- There may be problems from failing to account for the relationship of surface and groundwater.
- It is common that two-party transfers between agriculture and some other water user will affect several third parties, such as local communities, sport fishing, and environmental interests. Some institutional mechanism is needed to assure that all interests are protected.
- Market-based water transfers are likely to work better in places having extensive conveyance systems and storage facilities and with well-coordinated operations, such as California. For many other locations, such as New Mexico and west Texas, consider able experimentation with better organization of conveyance and storage facilities may be required to make short-term water trading work.

CONCLUSION

Water used in irrigated agriculture responds considerably more to price changes than water used by cities. Agricultural water right owners can use this price responsiveness to advantage by renting or leasing their water to cities or others who need wet water in periods of drought with no change in water right ownership. Legislation that defines water trading to be a beneficial use of water may be needed to remove a major institutional barrier to water conservation. Such legislation effectively provides information to agriculture of the real cost of continuing to use water in agriculture in the face of a high price that a city may be willing to pay. Legislation that promotes voluntary short-term water transfers could open up a market for agricultural water and increase profits to water rights holders who choose to rent their water to cities in a dry year. It could also reduce the cost to water buyers of securing needed water.

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WATER, PLANNING, AND ADMINISTRATION IN THE MIDDLE RIO GRANDE BASIN

W. Peter Balleau[76]

ABSTRACT

The Middle Rio Grande Basin is an historical center of water studies for scientific, operational and administrative purposes. The flow through the basin and the volume held in storage both are appreciably larger than required for present or foreseeable uses. The water limitations involve adapting the current pattern of uses to suit future conditions without trespassing on obligations to existing users in the basin and downstream. A flow of value to the old purposes and a flow of water to the new purposes is to be facilitated. Important objectives of the water planning process include an agreed listing of prior water rights that can be transferred to new purposes, and an agreed hydrologic model suitable for illustrating the effects on the basin. Improved science, management and administration in the future will provide water for a larger community with less impact on the environment of the Middle Rio Grande Basin.

INTRODUCTION

The Middle Rio Grande Basin (MRGB) between Cochiti Reservoir and Elephant Butte Reservoir is one of the best-documented hydrogeologic systems in the Earth's crust as reported at a MRGB workshop in February 1998 (U.S. Geological Survey or USGS, 1998). The impetus for the intensive study is wide recognition of the hydrogeologic system's management limitations. Interaction of the basin-fill aquifer with the

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[76] Balleau Groundwater, Inc., 901 Rio Grande Blvd. NW, Suite F-242, Albuquerque, New Mexico, NET: balleau@usa.net

surface-water system is a major concern. Prominent among the administrative and management concerns are water deliveries to Elephant Butte Reservoir thence to Mexico and Texas, prior water rights in the basin and background environmental conditions. Scientific research and application is producing new information and is confirming and refining the earlier understanding of the basin. The magnitude and variability of the water resource; its uses; the effects of development; and the administrative, planning and economic issues are becoming clear. Research on additional information now can be focused on the critical questions. This paper includes a hydrologic and administrative overview of the MRGB and a projection of a plausible future for the water resource in the Albuquerque Basin.

THE FLOWING RESOURCE

The yield of a water basin is counted in two hydrologic components; a flow component (rate) and a stored component (volume). The ratio of the two is the residence time for the system (volume/rate = time). Groundwater and surface streams have markedly different characteristics in this regard, and are used differently to take advantage of these characteristics. Surface water is of high velocity and relatively low volume with a quick flow-through period. A river flow pulse test in May 1996 traveled from Cochiti to San Acacia in 4.8 days (U.S. Bureau of Reclamation or BOR, 1997). Accordingly, Rio Grande surface water has a short transient time in the system and is highly variable and unreliable. It is used in priority to retain some certainty regarding baseflow supply for the early projects such as Pueblo and Spanish irrigation. Later users, with less certainty of supply, have built storage reservoirs or wellfields (Middle Rio Grande Conservancy District or MRGCD and the City of Albuquerque) to damp out the natural variation in surface supplies.

The historical trends in surface-water supplies are illustrated on Figure 1 showing the record of gaged river flow at San Felipe at the upstream part of the MRGB, and at San Marcial, the station measuring

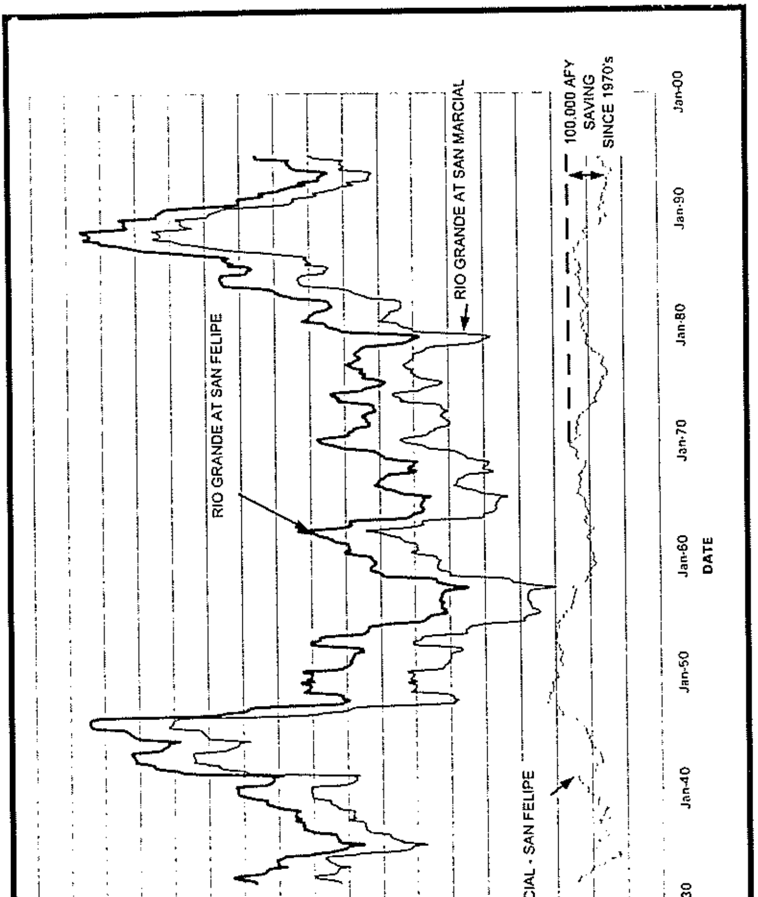

Figure 1. Historical Trends in Surface-Water Supplies

deliveries out of the MRGB. The difference between the two stations shows that the MRGB reach depletes the flow of the river between 320,000 acre feet per year (AFY) in the 1950s to 120,000 AFY in the 1990s. The San Juan-Chama Project has imported 51,500 AFY from 1972 to 1995 (Rio Grande Compact Commission Reports, 1972 to 1995). Municipal return flow adds another 60,000 AFY from basin storage. In recent decades, the net yield of the MRGB has increased by 100,000 AFY. The MRGB in the 1990s relies largely on local sources and uses only 120,000 AFY of the inflow to the basin for managed operations. The Rio Grande through flow is about 1.04 million acre feet per year (MAFY) (Thorn, and others, 1993). Local runoff from the 3,060-square mile MRGB generates about 227,000 AFY (Thorn, and others, 1993).

The groundwater flux is equivalent to natural recharge and discharge in the basin. The USGS has estimated the number as 140,000 AFY (Thorn, and others, 1993). The annual recharge is uncertain, but at any rate is a small percent of stream flow. A distinction is made between natural and induced recharge in the basin water account. The natural recharge rate is pertinent here. The captured discharge and induced recharge to the aquifer due to wellfield development are to be added to the natural rate of aquifer recharge and subtracted from the river baseflow.

THE STORED RESOURCE

The stored volume available in the basin includes the contents of the river channel, the surface-water reservoirs and the groundwater reservoir. Stored water is not static in either case, but is the volume that fills the system and continually is replenished by the flux components discussed above.

I estimate that the Rio Grande channel in the MRGB contains about 50,000 acre feet (AF) on a typical day (0.25 miles x 160 miles x 2 feet storage x 640 acres/square mile = 51,500 AF). The surface reservoirs that are dedicated to the MRGB include El Vado, Heron and some fraction of Abiquiu and Cochiti, with typical storage totaling about 600,000 AFY of MRGB contents (Ortiz and Lange, 1997) (Table 1).

Table 1. Surface-Water Reservoir Capacities

Reservoir	Capacity (AF)	Storage End of Water Year 1996 (AF)
Heron Reservoir	401,300	335,150
El Vado Reservoir	186,250	45,160
Abiquiu Reservoir	1,198,500	145,510
Cochiti Lake	502,330	56,560
Jemez Canyon Reservoir	172,800	18,110
Totals	2,461,180	600,490

The groundwater reservoir is the largest stored resource in the basin. A USGS model (Kernodle, in press) can be used to quantify the stored resource to various levels of drawdown. The surface area and recoverable specific yield of the model water-table zones indicate the volume contained in each foot of aquifer thickness. For the illustrative case of 400 feet of drawdown throughout the basin, the groundwater reservoir holds about 91 million acre feet (MAF) (Table 2) of recoverable water. In this estimate the drawdown is limited by the 400-foot threshold of Santa Fe Group subsidence (Haneberg, 1996), although drilling has shown potable recoverable water to depths below 2,000 feet (Brown, and others, 1996, and Shomaker, and others, 1994).

Table 2. Groundwater Reservoir Contents

	Area (Acres)	Specific Yield	Dewatered Thickness(ft)	Volume of Water (AF)
Albuquerque Basin Model	1,518,080	0.15	400	91,084,800
Bernalillo County	741,760	0.15	400	44,505,600

The productive fresh-water aquifers 400 to 2,000 feet below the water table can be developed by wells, and the drawdown caused by such development will not cause land subsidence until the loading of dewatered sediments exceeds the previous loading in the geologic development of the basin. Pleistocene unloading by sediment erosion in the Rio Grande Valley provides a 400-foot buffer before the loss of sediment buoyancy from dewatering matches or exceeds the pre-consolidation loads on the geologic column. Therefore, the volume of 91 MAF is calculated for the Santa Fe Group aquifer space above that subsidence threshold. The recent alluvium of the Rio Grande floodplain, however, is not protected by pre-consolidation and is subject to rapid subsidence. For interest, the stored aquifer volume to 400-foot depth is about one fourth the volume of Lake Erie (Shiklomanov, 1993). The stored aquifer source is equivalent to about 100 years of average river flow, and is 150 times the total surface-reservoir contents. The physical water resource available to the MRGB is summarized in Table 3.

Table 3. Magnitude of Water Resource in the Middle Rio Grande Basin

	Surface Water	Groundwater	Total
Flowing Resource (AFY)	1.2 million	0.14 million	~ 1.3 million AFY
Stored Resource (AF)	0.6 million	91 million	92 million AF
Residence Period (years)	0.5	650	70

About one MAF of groundwater storage has been depleted through 1992 (Thorn, and others, 1993). Despite reports of a locally diminishing aquifer (City of Albuquerque, 1997), the aquifer storage remains the major source of available water in the MRGB. Four major applications to appropriate 80,000 AFY of groundwater for future needs are pending in early 1998 to serve the City of Albuquerque, suburban cities and the County of Bernalillo.

USERS IN THE MRGB

The water budget of the MRGB includes consumptive use by natural background and by man-made projects. The USGS (Thorn, and others, 1993) values are about 150,000 AFY for background evaporation from riparian vegetation and wetlands, and about 120,000 AFY for man-made beneficial uses, largely from irrigation. Figure 2 shows the water-balance components for the MRGB in the early 1990s. Values are summarized from Thorn and others (1993) and from Kernodle and others (1995). Consumptive use (CU) of water is in two categories, managed and background. Managed uses have water rights administered by the New Mexico Office of the State Engineer (OSE). Background uses are Mother Nature's. Surface-water CU of about 270,000 AFY is a minor part of the overall surface-water and groundwater availability.

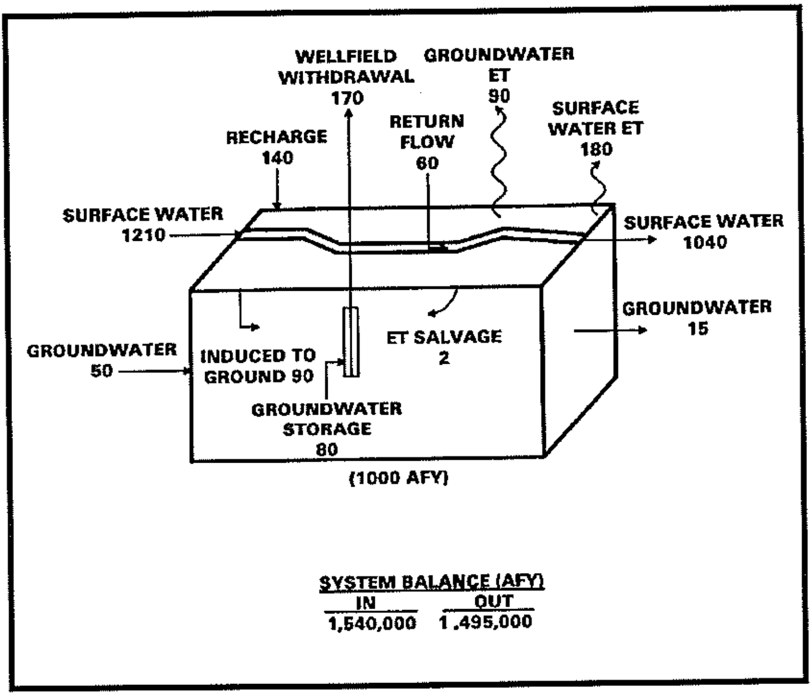

Figure 2. Water Balance of the Middle Rio Grande Basin

Wellfield withdrawals for all purposes were estimated as 170,000 AFY in 1994 (Kernodle, and others, 1995). About 80,000 AFY of the withdrawn amount is derived from the stored groundwater; the remainder is induced recharge from the surface-water system.

Overall physical availability is not a management concern when usage is about one third of the renewable surface-water supply and one thousandth of the stored volume. The limitations lie in the specific effects of development on the local structures and the external administrative requirements for water rights, compacts and treaties. For example, water-table drawdown in the floodplain alluvium on the east side of downtown Albuquerque has exceeded 50 feet and is implicated in foundation subsidence for structures in the valley (Albuquerque Journal, January 7, 1994). Microchip manufacturing, and other new projects, are constrained by accounting for effects on required pass-through deliveries to Elephant Butte.

EFFECTS OF DEVELOPMENT

The response to surface-water development is seen quickly at downstream points in the watercourse on a time scale related to the flow-through period of a few days. The response to groundwater development is retarded by the large storage in the aquifer system. The time scale of response to aquifer stress is related to the hydraulic properties (diffusivity[77] and distance from the stream) and may range from days to millennia. A higher transmissivity or a lower storage coefficient for the aquifer being developed will cause a quicker response in the interrelated stream. Transmissivity, indicating how readily water is transmitted through the aquifer under a unit hydraulic gradient, is measured as the volume of water transmitted per unit of time through a unit width of the aquifer ($L^3/T/L$). Greater transmissivity means greater response at the interrelated stream. Storage coefficient, indicating the fraction of the volume of dewatered aquifer space that

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[77] Hydraulic diffusivity is the ratio (transmissivity/storage coefficient) or (hydraulic conductivity/specific storage)with dimensions (L^2/T) that indicate the rate of growth in the area of response.

yielded water, is a dimensionless ratio. Smaller storage coefficient means greater response at the interrelated stream.

The water produced from wells in the MRGB is accounted for by depletion of two components, stored groundwater and interrelated surface water. A growth curve, such as indicated by the USGS model (Kernodle, in press) of the basin, shows the transition from initial aquifer-storage depletion to ultimate induced surface-water depletion. Figure 3 illustrates the curve simulated by the USGS model for two example wellfields located one-mile and six-miles west of the river. After 100 years, about 20 percent of the well water is derived from the stream regardless of distance from the stream. For these illustrative conditions, wells deplete the Rio Grande to a lesser fraction and salvage evapotranspiration to a greater fraction of withdrawals. The surface-water impact consists of direct depletion of river, drains and canals, and on indirect interception of surface water that feeds riparian vegetation or associated evapotranspiration from the shallow water table. The salvage of evapotranspiration losses does not add to the net river depletion. The evapotranspiration salvage affects background environmental conditions, and the Rio Grande depletion affects the water right and compact concerns. Different curves can be simulated for different wellfields operating at different times in the basin. Less water can be salvaged from evapotranspiration in a developed basin than in a waterlogged undeveloped basin.

The shape of these growth curves for effects on the Rio Grande is critical to the administrative planning issues regarding prior rights and downstream delivery. The stress-response curves depend on hydraulic characteristics of the aquifer and the stream alluvium that are necessarily uncertain. Part of the planning question is to decide how well-defined that stress-response curve must be for practical management. The curves on Figure 3 show induced recharge in response to development, which must be distinguished from natural recharge throughout this discussion.

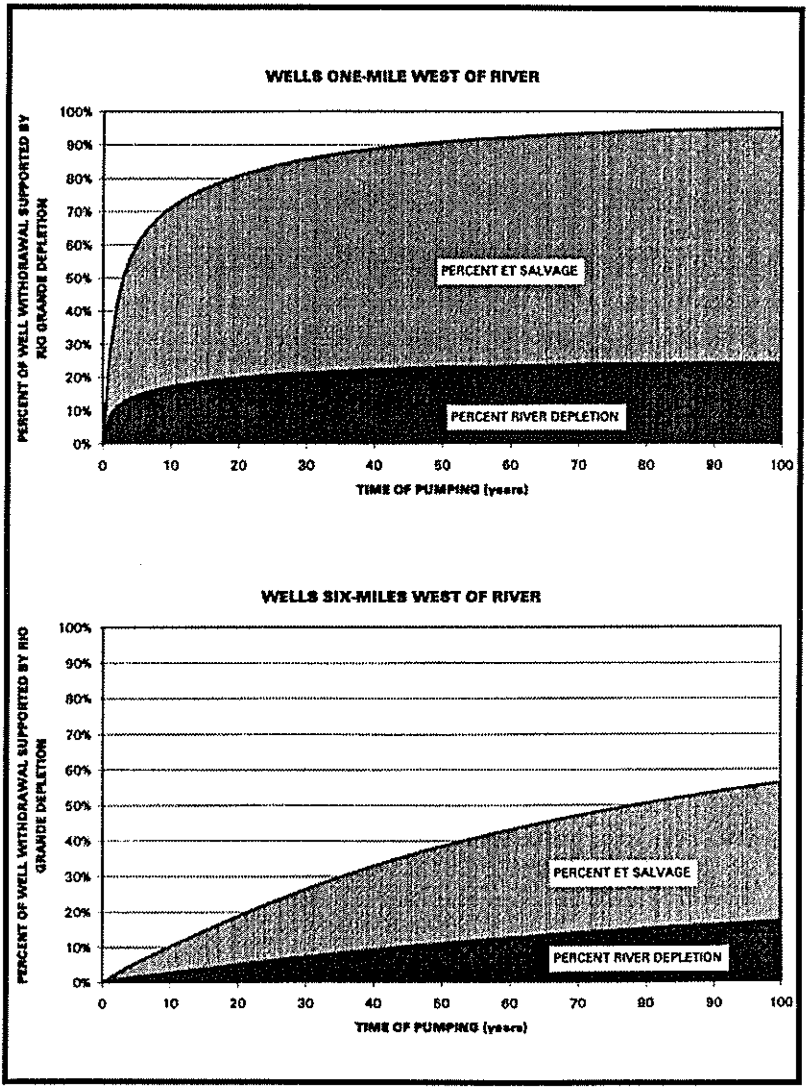

Figure 3. Illustrative Transition Curves from Initial Aquifer Storage Depletion to Induced Surface-Water Depletion.

Induced recharge of river water by well development must be offset to maintain the flow through the MRGB. If wells induce about 20 percent of their production at 100 years, then wells add five times as much to the net yield of the basin as do surface-water diversions. The great benefit to users of water from developing stored groundwater should not be neglected in planning the future of the MRGB.

Much of the current intensive study is on the question of hydraulic characterization (McAda, 1996). The sensitivity of the response curves to additional information and to present uncertainty is being evaluated (Mr. John Stomp, oral communication, February 1998). A pertinent principle of hydrologic modeling is that the level of detail in the model must fit the requirements of the question being studied. Practical models necessarily compromise the identification of parameters with the near-infinite complexity of the field situation. Parameter estimation follows parameter identification. As of 1998, the suite of parameters that control the MRGB still are being identified. Some field data may be proven irrelevant while pertinent data are neglected unless sensitivity is evaluated early in the process.

The hydrologic response to water development has benefits and penalties that can be accounted directly to a project, directly to other affected projects, and indirectly to external effects. Agriculture, for example, often substitutes for riparian consumption on the same acreage (Natural Resources Committee, 1938). An applicant for approval of a new water management operation seeks new benefits, a protestant seeks to avoid new costs and the administrative officials seek to promote public values such as efficiency, conservation and community (Tarlock, 1996). Some of the types of effects to be assessed and an appropriate management response involve, for example, a surface supply shortage which can be addressed by a market exchange with administrative review, aquifer depletion which should be considered a beneficial investment for the future and the hazard from land subsidence which requires all users to manage the local groundwater level by site specific drawdown and recharge operations.

LIMITS OF WATER DEVELOPMENT

Some limits to growth of water consumption in the MRGB, including physical and administrative limits, are listed in Table 4. This listing tends to confirm that the MRGB water use will reach a water rights and compact limit at about 300,000 AFY before it reaches a physical limit.

Table 4. Physical and Administrative Limits on Water Use in the Middle Rio Grande Basin

Irrigation Water Rights	126,300 AFY (OSE, 1983)
Municipal Water Rights	96,000 AFY (Balleau, 1994)
Rio Grande Compact (Average Year)	261,000 AFY (New Mexico Statutes 1978 Annotated, 1997)
San Juan-Chama Project Imports	51,500 AFY (Rio Grande Compact Commission Reports, 1972 to 1995)
Tributary Inflow	227,000 AFY (Thorn, et al, 1993)
Rio Grande Inflow	1,210,000 AFY (Thorn, et al, 1993)
Virgin Flow, Predevelopment	3,060,000 AFY (Natural Resources Committee, 1938)
Aquifer Stored Resource	91,000,000 AF

Today's use of water for the established pattern of agricultural, background and municipal purposes cannot grow to a larger net amount of water without new interstate agreements. Instead of growing, the established patterns are shifting as they have in the past, with increased municipal and industrial uses and reduced agricultural and background use. Transfers of use are the order of the day for surface water. Conversion from natural background uses to managed permitted uses is a major historical trend. Abundant stored groundwater remains to be appropriated where transfers can offset associated surface-water effects. Reliable knowledge of the hydraulic relationships among the sources of water and categories of use is required for the transfers to proceed with a full accounting of the internal and external project effects. Today's merely adequate models are sufficient for today's findings and decisions without waiting for tomorrow's superior models. Applied hydrology has an exceptionally demanding task in the MRGB in defining the relationships in the system.

WATER-RIGHTS ADMINISTRATION

Water-right owners have the mission of creating benefits from their water operations and avoiding costs imposed by other water operations competing for the same water. A regulatory agency has the mission of examining and approving or denying applications for proposed water-management operations based on legal standards. The legal standards include impairment of existing uses, resource conservation and public welfare. In this paper, I distinguished the roles as management and administration. It may be useful to view management as looking after the narrow proprietary account, and administration as looking after the broader public-interest account. Other commentators extend management to include the public policy-setting which is subsequently administered by agency officials (Corker, 1971). However, if management is what owners do to enhance project benefits, then government agencies generally do not "manage the water resource."

Albuquerque, an owner and operator, has developed an Albuquerque Water Resources Management Strategy (City of Albuquerque, 1997) to enhance benefits to the municipal users of water in the basin. The OSE, the administrative agency, has developed a task force draft policy on administrative criteria (OSE, 1994). The Albuquerque Water Management Strategy, for example, will be examined in terms of OSE administrative criteria. The criteria are not yet officially adopted, but generally call for an end to new appropriation in areas where water levels are declining or will decline faster than a rate of 100 feet per 40 years, and require that the induced depletion of the Rio Grande be fully offset. Offset can be by return flow or transfer of rights or imported water. The implied objectives are to extend the lifetime of the stored resource, and to maintain status quo on the Rio Grande flow. The criteria are designed to administer an unadjudicated basin, i.e., the priority of rights is not a consideration.

The priority of water rights is not administered in the MRGB because the rights are unadjudicated. No enforceable Court decree of the priority, diversion points, source, amount, place or purpose of rights has been made. The OSE is not empowered to decide priority, therefore, the OSE cannot administer priority, but treats each application for permit as the junior right with all existing rights as senior but of equal administrative standing. In a transfer application, for example, a valid recent permit is as good administratively as a valid older right originating from Spanish or Pueblo times. The status quo as of 1956, when the Rio Grande underground basin was brought under administration (OSE, 1995), however, does not protect priority by distribution of water in periods of shortage according to seniority of appropriation. A decree of water rights provides the initial condition from which administration can ensure that new uses obtain water with a full accounting of impacts on the issues regulated. The issues specifically, are impairment of other water uses, resource conservation and public welfare.

Many of the issues of MRGB planning would be removed by having a listing of water-rights quantity, location and seniority. The American Society of Civil Engineers (1987) advised that "The major water adjudications within a hydrologic unit can, if properly handled, offer a solution to many organizational and financing problems which are otherwise extremely troublesome."

A central administrative objective is to maintain the baseflow of the Rio Grande at its 1930s Rio Grande Compact condition. Two changes since those times have affected the yield of the basin, the imported San Juan-Chama Project water and the development of groundwater storage. About 120,000 AFY have been added historically to the river from the two supplementary sources (Thorn, and others, 1993 and Rio Grande Compact Commission Report, 1972 to 1995). The aquifer storage has been delivered downstream in excess of requirements partly because of the intentionally conservative calculation in the OSE administration of stream depletion from wells. The San Juan-Chama water is delivered downstream in excess because accounting is made at Otowi, but is not tracked in the MRGB. Figure 4 shows that 2.2 MAF, mostly since 1980, has been spilled from Elephant Butte due to deliveries in excess of requirements. The MRGB is entitled to capture and use that water under the Compact. Overly-conservative administration of the river has reduced the stored water reserves for the MRGB. The State of Texas complains that the spilled water is unmanaged and of little benefit to them (Keyes, 1996). One planning question is whether overstating stream depletion in OSE administration of well permits helps or hurts New Mexico.

WATER COSTS

The cost of water in the MRGB in 1996 is indicated in Table 5. The value of water in the MRGB was thoroughly studied in Brown, and others (1996). Assuming that price reflects value, the current pattern of allocations can be shifted to municipal and commercial use from agriculture with considerable value added to each purpose of use.

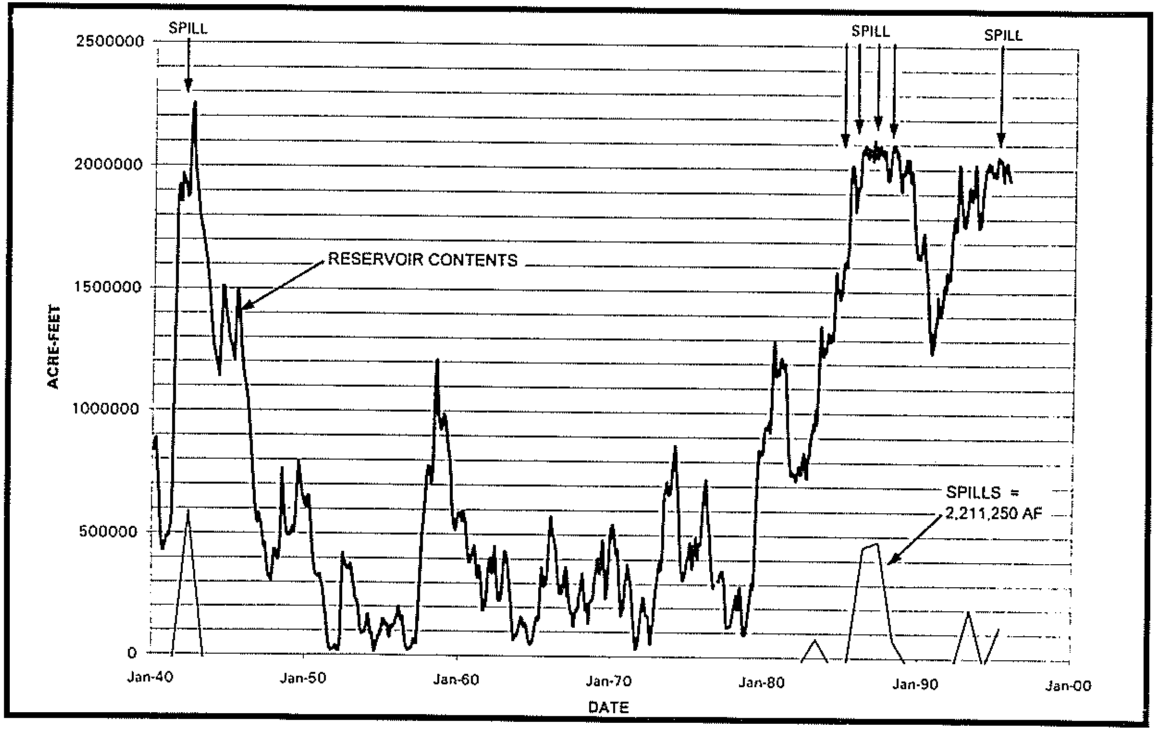

Figure 4. Elephant Butte Reservoir Contents and Spills

Table 5. Cost of Water in the Middle Rio Grande

Agriculture	
MRGCD	$9.33/AF (1996)
City of Albuquerque	$10/AF (1996)
Non-Agricultural (Secondary Lease)	
San Juan-Chama	$39.14/AF (1996) $43.17/AF (1997)
City of Albuquerque	$41.02/AF (1996)
Public Supply (City of Albuquerque)	
Unit Cost (Commodity Charge Plus State Conservation Fee)	$296.21/AF (1996)
Water Users Pay Different Rates Based on Meter Size and Customer Class (1996)	
Residential	$317 to $321/AF
Commercial	$334 to $341/AF
Industrial	$401 to $425/AF
Institutional	$330 to $337/AF

Transfer to a higher value purpose of use requires a corresponding payment to the owner of the former purpose of use. Also required is an administrative examination of accounting of effects on rights, conservation of the resource and public welfare. Transfers that account for all internal and external effects of a new water operation are desirable.

WATER PLANNING

A basin-wide regional water planning effort is underway in the MRGB with participation of an Action Committee of managers, advocates and experts. The effort intends to meet the guidelines of State regional planning (New Mexico Interstate Stream Commission, 1994), and perhaps to go beyond that and outline a comprehensive water plan for the basin. The role of water planning is widely acclaimed (Titus, 1998), and sometimes disparaged (Ms. Ann Rogers, oral communication, November 8, 1997). Water planning, in fact, cannot usurp the future manager's function of determining how to produce the most benefit from water to a future project account, neither can it decide how a future administrator will evaluate resource conservation or public-welfare interests. The last New Mexico Water Plan (BOR, 1976) forecast uranium mining, power, and oil and gas production as the major growth in state-wide water use. Post-audits show that projections often are wrong about sectors and levels of future water-use activity (Konikow, 1986). Barrow (1998) in a critical review of water plan implementation finds that "Various forms of river basin development planning and management have been applied in many countries. Unfortunately, the results have been disappointing." If planners cannot foresee future demands and valuations, then what is the role of MRGB planning?

Two goals for the planning effort are suggested. One helpful goal of the MRGB regional planning effort would be to agree on the listing of historic priority and amount of rights in the basin. A planned, negotiated, comprehensive adjudication is needed that can be adopted by court decree. Future managers and administrators will appreciate inheriting a decree of rights that allows them to proceed with transfers of valid rights to accommodate development in the basin while protecting those valid rights.

A second helpful goal of planning is an accepted model of the interrelationships of hydraulic stresses and responses in the basin, for the purpose of evaluating changes in terms of effects on the decreed rights.

Today's planners should not attempt to define future water uses or quantities for those uses. They should find agreeable mechanisms for moving water and compensatory value to satisfy changing demands.

INFORMATION NEEDS

Abundant information on the hydrology of the basin is becoming available. The MRGB study workshop February 10-11, 1998, displayed progress on mapping, geology, geophysics, drilling, magnetics, seismic history, geographic information systems, climate, land use, cartography, geochemistry, modeling, dating and tracing groundwater, temperature, field tests, recharge rates, unsaturated zone and mass-balance studies. Hydrologists know that the near-infinite detail in the Earth's crust cannot be characterized fully, therefore, we ask "What do we need to know to satisfy the applied hydrologic objectives?" I suggest that practical objectives and attainable information are along the lines listed in Table 6.

Success in applied hydrology usually comes from using the abundant information available in an observational approach. The increment of new data added from intensive effort each year invariably is less than the accumulated data recorded in the past. The Albuquerque Basin studies should examine the sensitivity, in terms of practical results, to the gain in new information in comparison to the better use of old information.

A HYDROLOGIC PROJECTION

The Rio Grande High School class of 2000 will have its 40th reunion in the year 2040, which is the current planning horizon for State water studies. What will water operations in the MRGB be like in 40 years? My projections include some hopeful speculation.

The three percent annual growth in productivity of the economy (Atack, 1995) will make most goods costs 30 percent of today's real cost. Water works will be less productive (U.S. Economics and Statistics Administration, 1995), but will be provided at 66 percent of today's real cost, that is, twice the relative future cost of other goods. Basin population may double (McDonald, and others, 1989). Water use will shift

Table 6. Information Needs for Practical Objectives

Objective	Information Requirement
1. Delivery obligation to Elephant Butte	•Comparison of Compact index curves to 1990 conditions. •Monthly flow data at river and at diversions. •Annualized system response to managed diversion/operation. •Separation of natural and induced river-depletion response to managed well withdrawal/ re-charge operation. •River stage (stress) versus seepage and aquifer head (response) relationship. •A river boundary stress test for comparison to the aquifer stress tests. •Identify area of influence of aquifer development.
2. Administration of priority for security, ease of transfer and reliability of supplies	•A negotiated Court decree of priority, amount, diversion point, place and purpose of uses. •Hydrographic survey and historical uses inventory.
3. Environmental baseline protection	•Same as 1 above.
4. Maintain community objectives	•Obtain statement of community objectives through basin planning process.
5. Understand effects of alternative wellfield development	•Examine calibrated model results for basin wellfields at alternative sites and rates from Cochiti to Socorro.
6. Understand water-quality and yield patterns in aquifer	•Drill and sample one well per township throughout the basin to the depth of the potable water limit.
7. Model calibration	•Model calibration requires observational history matching of the response to historic development. The best three-dimensional data set in the basin is the Intel daily monitoring data for 15 constructed wells and 15 existing wells since 1995. •Short-term stress and response tests cannot provide the information contained in the 50-year observational history of stress and response. The model that matches long-term history is the best for projecting the long-term future.

from today's approximate thirds for municipal, agricultural and environmental categories to two-thirds municipal, one-sixth each for agricultural and environmental. Conservation will have had an initial, but not a long-term, impact on per capita water use. The benefits of improved water facilities and management will exceed the costs.

The available surface-water supply will be the same. Discussions on adding water leasing provisions between the States will be in progress. Groundwater will have depleted an additional four MAF from the 100 MAF aquifer reserve at the average rate of 100,000 AFY from storage. Wellfield withdrawals will be steady at 200,000 AFY with one half derived from the surface stream. Basin wellfields will be more extensive and further from the river. Less drawdown over a greater area of the basin will avoid a concentrated cone of depression in water levels. The Albuquerque Northeast Heights wellfields still will be operating but with new equipment at deeper pump settings at about the same rates as in the 1990s. Wellfield depletion of the river will be offset by full San Juan-Chama Project imports and by leasing of old irrigation rights. Regional integration of water operations will not succeed. Each County will have an independent water-system operation. Negotiated operating criteria will avoid conflicts.

Albuquerque Metropolitan Area Flood Control Authority and MRGCD drains and canals will be buried and covered for safety, mosquito control, efficient pressurized operation and for recreational use of the rights of way (bicycle, equestrian, walking, etc.). Water will be injected into the floodplain alluvium to maintain the water table at a controlled level and prevent further subsidence in downtown Albuquerque.

The Federal agencies will provide water information in the form of data, interpretation and calibrated model projections on each watercourse, conveyance structure, diversion point, evapotranspiration, habitat and three-dimensional aquifer level. The data are updated in a real-time system model with on-line public access to diversion, consumption rates and return flow water quality. A public-access database of permits, priority and discharge plans will be available for comparison to actual use. Monitoring is by interested citizens who query networked hydrologic information systems data and rights in their neighborhoods. Federal officials provide information, State agencies administer permits according to court decree and private parties manage their operations for the best value.

The majority of river flow, about one MAFY will continue to be delivered downstream. In doing so, the deliveries are scheduled and controlled to provide valuable services for riparian, environmental, recreational and public welfare benefits from the waters passed through the MRGB. Water rights for the small additional depletions due to those services have been acquired by public agencies and private groups. Elephant Butte no longer spills because the spill water is retained for use in the MRGB.

New water demand is supplied from the list of initial water rights adopted by stipulation among the major interests and decreed by the court. The initial list of rights is continually updated by transfers. Water operations managers routinely evaluate their plans, the capacity to pay value to a previous right owner and the explicit administrative criteria for resource conservation and public welfare that were agreed upon in the court stipulation.

New developments that require water apply at the one-stop OSE where a catalog of decreed water rights and subsequent administrative actions documents the current status of all water-use rights in the State. Any degree of reliability is available for the new development from the pool of identified rights with priority offered in the on-line catalog.

High priority rights are available at a substantial premium. The surface-water reservoirs and the abundant aquifer-storage reserves and integrated operating rules have made water shortage rare. Reservoir releases will be used to offset streamflow induced into the extensive wellfields.

The rare shortage in a multi-year drought will be provided for by leasing of Pueblo reserved and old Spanish historical rights. Annualized payments for intermittent use of old prior rights have eclipsed the revenue from gaming in the valley. The Pueblo and mountain tributaries with enforceable senior priorities have been maintained as required by Court decree. Wastewater will be treated and extensively reused. Permitted discharges maintain background conditions through the Pueblo stream reaches and wildlife refuges. Effluent pipelines have been constructed to by-pass sensitive recreational and environmental reaches of the stream. Some effluent is conveyed to Elephant Butte Reservoir to take advantage of its mixing zones and assimilative capacity.

In the year 2040, New Mexico remains the oldest and happiest center of habitation in North America and a center of advanced hydrologic science renown throughout the world.

CONCLUSIONS

1. The water resource in the MRGB consists of about 1.3 MAF of annually renewable water, and 92 MAF of stored reservoir contents. Both the renewable and the stored resource exceed the current and projected level of use in the basin. The stored resource in the aquifer is large and its continued use is essential for the future of the basin.

2. Surface water consumed and depleted from the MRGB is about 270,000 AFY for artificial and natural background uses. Since the 1970s, the basin has been conveying a larger fraction of inflow to Elephant Butte than in earlier decades.

3. Uses are not limited by the physical supply, but by compact and treaty agreements to deliver most of the physical supply to downstream sites. The working principle for the future involves transfers of value to existing users and corresponding transfers of water to new users.

4. The hydrologic relationships between changes in patterns of use and the responses at other parts of the hydrologic system must be understood for checking whether proposed changes are acceptable to the MRGB community. The general relationships are understood. The degree of site-specific precision required in characterizing the relationships is being studied. It is possible that we know enough in 1998 to manage properly.

5. Managers and owners of water operations must remain able to propose beneficial new project operations that enhance the value of water in the basin. The ability to adapt to new opportunities is aided by clear administrative criteria. The greatest shortcoming in basin administration is the lack of a court decree of water-right priorities and amounts. Without a starting position, water cannot move.

6. Planning should be directed toward:

    a) a negotiated comprehensive agreement on the priority listing of water rights for adoption by court decree, and
    b) an agreement on a serviceable quantitative model of the basin for evaluating the effects of applications for new water permits.

7. Today's planners should not attempt to define future water uses or quantities for those uses. They should find agreeable mechanisms for moving water and compensatory value to satisfy changing demands.

8. Water to serve environmental, recreational and public welfare needs can be scheduled from the one million AFY already passing through the basin. Rights for relatively small additional depletions due to re-scheduling the flows may be acquired from the decreed list of prior rights.

9. Technical studies should be selected in terms of practical advancement of the administrative questions, and should apply the abundant historical data for model calibration.

10. The management, administration, and science of the basin will be better in the future, and will support a larger community of users with less impact on the background environment.

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WATER CONSERVATION IN NEW MEXICO AGRICULTURE

Carl Barnes and Robert Flynn[78]

INTRODUCTION

"Water conservation!" What the term means depends on whom you ask. To some, it means saving water so other users can tap into the source. To others, it means reducing use in order to allow more water in the streams and rivers for instream flows and downstream users. This article focuses on an agricultural user's perspective. It is our belief that water conservation is best defined as optimal use of water for the welfare of New Mexico citizens. We admit it is a rather vague and far reaching description but we also believe the subject is vague and far reaching. Issues range from the appropriateness of over irrigation as a method of recharging the underground aquifers to those who promote the lining of every irrigation supply canal and lateral ditch, encasement of all supply sources and the use of buried drip irrigation systems as the best conservation practices.

Dryland agriculture, or naturally irrigated agriculture, is also active in the arena of optimal use of available water supply. Arguably, dryland producers might have the highest vested interest in water conservation since their survival literally depends on their degree of success. Since many thousands of acres are involved and millions of tons of food and fiber are produced, water conserving and harvesting techniques are essential to our survival.

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[78] Professor of Agronomy & Assistant Professor of Agronomy, respectively, New Mexico State University, Department of Agronomy & Horticulture, Agricultural Science Center, 67 E. Four Dinkus Rd., Artesia, New Mexico, e-mail: artesia@nmsu.edu

For purposes of this discussion we will address practices that enhance the efficient use of water and leave the debate over the philosophical issues to others.

BASIC IRRIGATION TECHNIQUES

We believe that to understand the issue of water conservation in agriculture, one must have an understanding of basic irrigation practices. Perhaps the oldest and most basic method of applying water to agricultural lands is "flood" irrigation. As the name implies, irrigation water is applied to a soil surface and allowed to move across that surface via the inertia of gravity, that is, flooding. In many parts of the world, flooding can be accomplished by a simple dam across a stream and a shallow lateral ditch to guide the water to its destination. This method, in its simplest form, requires low capital investment and was, thus, very appealing to early day settlers and is still used by those with limited capital resources. Collectively, flood irrigation represents the most widely used irrigation technique and many improvements have been made through the years. Quantities of water delivered are dependent on soil moisture prior to irrigation. Typical amounts range from 2" to 10" in one irrigation.

"Sprinkler" irrigation is a term applied to systems that utilize pressure generated at the point of final delivery to dispense water through the air in man's attempt to simulate rainfall. The major benefit of this system is the reduction in percolation losses that are encountered with some flood irrigation systems. These systems are more capital intensive than the basic flood systems. Sprinkler systems are subject to high evaporation losses under some conditions but allow for efficient delivery over uneven terrain. Solid set or sideroll systems generally will be used to deliver 4" to 8" of water in one irrigation. Pivot or linear move systems deliver water based upon how quickly the system moves over the land and the gallons delivered over that time.

"Trickle" or "drip" irrigation is a term applied to a method of water delivery that, like sprinklers, utilizes pressure through small openings in polyvinyl tubing to emit water in minute amounts on an almost daily basis to replenish water used by the crop and avoid losses from deep percolation. Systems that utilize buried lines are perhaps the most efficient methods developed to date as they effectively eliminate losses from surface evaporation. Drip systems are generally more capital intensive than basic flood and sprinkler systems. Arguably, this method is no more capital intensive than some of the more sophisticated flood and sprinkler systems. Typical drip systems deliver 1/10" to 4/10" per irrigation.

To fully grasp the significance of agricultural water conservation, a person must understand that plant growth is dependent on water and sunlight. Sunlight provides the necessary energy for biological processes and water serves as the transport agent for nutrients from the soil and air and for cooling through evaporation. The collective process of transpiring water through the plant and evaporation from the plant and soil surface is called evapotranspiration. We make this point in order for you to understand that the amount of water required for evapotranspiration is largely dependent upon the climate and the plant species involved and there is relatively little that can be done to reduce this water requirement. However, there are genetic and chemical enhancements that can decrease water demand. From the perspective of agricultural production, the areas for effective "water conservation" lie in reducing evaporation from the delivery systems. Improving uniformity of application in order to reduce deep percolation losses may result in a reduced water requirement for an individual user although it may not result in savings for the overall water supply since one user's deep percolation loss may well be another user's supply.

WATER CONSERVING AGRICULTURAL PRACTICES

Flood Irrigation Techniques

We will start our discussion with practices associated with flood irrigation. Aside from harvesting rain by a system of terraces or cisterns, flood irrigation was the earliest form of irrigation and dates back to Biblical times. Those primitive systems were reasonably efficient with diligent care and an experienced irrigator. However, as the American agricultural revolution came upon the scene in the twentieth century, the drive to always improve efficiency and increase production per worker made changes inevitable. Producers working with agricultural engineers began to study and develop ways to apply water more effectively. Agriculture began to become familiar with terms like application efficiency, consumptive use, and peak demand. The southwestern United States became a leader in irrigation technology as agriculture in this area is faced with limited water supplies and high water demand. Government cost-sharing programs stimulated improvements in irrigation systems across the region. System designs that considered the appropriate volume of water delivery to the correct land mass to maximize application efficiencies became standard practice. Soil infiltration rates, length of run, percolation losses, and leaching requirements also became commonplace in the irrigated farming community. Management practices such as bench leveling, concrete lining of ditches, and use of siphon tubes and gated surface pipe were all practices that became common to control water flow. More recently, solar powered surge valves have been used to provide a mechanized way to automatically provide sequential alternating applications of water to a given area. Surge irrigation takes advantage of soil swelling upon wetting to close the porous spaces in the profile and cause the water to move quickly over the surfaces nearest the water outlet, thus improving the uniformity of the application over the entire area. Perhaps the most efficient flood systems come with the use of laser controlled land planes. Land planes have been in use for generations in the irrigated southwest as irrigators sought to improve the topography of the soil surface and gain better control of their precious resource. The advent of the laser controlled land planes brought this technology to a new level of competency that was only dreamed of in days past.

Sprinkler Irrigation Techniques

Sprinkler irrigation requires induced force resulting in water being propelled through the air from the point of delivery to its final destination on the soil surface. The earliest versions of this technology in the United States were portable, hand-moved pipes equipped with periodic outlets outfitted with rotating heads that delivered a pulsating stream of water. This technology improved the application efficiency in areas where, for a variety of reasons, it was not desirable to modify the soil topography and use flood irrigation. A later device, in essence, took this hand-move system and utilized the pipe as an axle in a wheel and coupled several together in something referred to as a side-roll system. This system was not more efficient from a water application point of view, but was more labor efficient since one person could move this system to the next set and have it quickly operating again. As its name implies, the system is rolled sideways across the area to be irrigated but is stationary during the time that water is delivered. The next progressive development in this technology was the advent of the center pivot system. This name is very descriptive and is an enhanced modification of the side-roll system where the water source is in the center of the area to be irrigated and the system revolves continuously around that point as water is being applied. As this technology has developed, there has been an increase in application efficiency by placing the sprinkler heads closer together, releasing water immediately above the plant canopy. The closer the nozzle is to the soil surface, the greater the reduction in water losses due to evaporation when compared to conventional impact heads that throw water greater distances through the air. A further advancement of this technology uses "drags" that release water directly onto the surface of the soil taking advantage of reduced evaporation similar to flood irrigation and the increased efficiency of the sprinkler concept of keeping the water contained until it reaches its final destination. Drop nozzles operate at a lower pressure than conventional impact sprinklers and at a lower cost.

Drip Irrigation Techniques

"Drip" or "trickle" irrigation is applied to those system that use polyvinyl tubing equipped with emitters that deliver very low volumes of water. Dependent upon the water demands of the crop, these systems are operated to deliver water very frequently in an attempt to maintain soil moisture at an optimum range for plant growth and minimize moisture stress. The first of these systems was used in high value human food crops and were mostly piping systems that were on or very near the surface of the soil. Their advantage over flood and conventional systems was reduced evaporation and deep percolation losses with generally increased production with less total water due to the optimal moisture conditions maintained in the root zone. Most flood and sprinkler systems apply water on a relatively infrequent basis resulting in periods of overly saturated soils followed by a short period of optimal moisture conditions leading to some amount of stress prior to the next application. Drip irrigation systems overcome that scenario. With the advancement of this technology, primarily in the development of self-cleaning emitters and more durable tubing, drip systems are now being buried 10 to 20 inches below the soil surface in permanent installations that allow for cultural operations and crop rotation without annual removal or replacement of the tubing for the traditional large acreage crops such as alfalfa, corn, and cotton. The burial of these systems has also enhanced water savings by allowing for crop irrigation without wetting the soil surface thus effectively reducing the evaporation component of irrigation to zero. With this significant water savings, researchers and growers alike are finding savings in the range of 25-50% over other more conventional irrigation methods while at the same time maintaining or obtaining an increase in plant productivity. The major disadvantage is the cost of the system. However, drip systems are not significantly more expensive than the top of the line center pivot systems. As water becomes a more valuable commodity, savings offset the cost of these systems.

Dryland Farming Techniques

An often forgotten, and monumentally important, area of water conservation are those practices utilized in the naturally irrigated agricultural community. This segment of our social and economic community literally involves millions of acres and thousands of tons of food and fiber production. From the standpoint of the impact to society, we cannot overlook this most hardy breed, the dryland farmers and ranchers. In order to survive, these individuals have been forced to learn to live in harmony with nature and take advantage of each opportunity. Few of us can recant the days of the great dust bowl era in the central plains section of our country but history books recorded the devastation that resulted from not understanding the harshness of the land. As a result of those experiences of our fathers and grandfathers, we have developed a more "user friendly" attitude. Practices such as organic mulches to protect the surface of the soil from wind and water erosion and at the same time increase the infiltration rate of rainfall have been embraced as we capture a higher percentage of that water supply for our crops.

Ranchers have learned to employ some of the same principles by not overgrazing rangelands. More sophisticated techniques are in use by crop producers and include such practices as contouring rows perpendicular to the slope of the land that create mini watersheds to capture a greater percentage of water by allowing more time for infiltration. "Furrow-diking" is another modification of these mini barriers to capture precipitation. This technique uses small mounds of soil placed in the furrows between crop rows to prevent or slow the movement of water down a slope during high intensity rain events. Sometimes these dikes are used in conjunction with sprinkler irrigation.

More drastic measures are needed to cope with limited water supplies in more arid regions. Reducing plant stands is a common practice in the high plains that realized the reduced production potential from dense stands and allows each plant to harvest water from a larger area. An extension of this technique is to plant in a pattern referred to as "skip-row." This procedure results in an uneven planting pattern that again provides more root zone for each plant. "Summer fallow" is a practice that results in crops being grown in alternate years. During the non-crop year, vegetation is prevented from growing either by cultural or chemical means and the water supply is stored in the soil for use by crops, effectively utilizing two years precipitation to produce one crop.

CONCLUSIONS

A historical review of agricultural practices readily reveals the constant and continuing efforts being made to become more and more efficient in all aspects of production. This statement is nowhere more evident than in the case of water conservation. Millions of dollars have been spent on various conveyance system improvements, land-leveling activities, and the ever advancing mechanical innovations to improve irrigation efficiencies. Agriculture, as a socioeconomic entity, is and has been a good neighbor to us all. Agriculture, particularly in the arid southwestern United States, is the caretaker of the water supply and will continue to provide the water required for industrial and municipal needs. At the same time, agriculture utilizes the most modern technology available to provide food and fiber for an expanding world population.

THE HIGH PLAINS (OGALLALA) AQUIFER: MANAGEMENT AND DEVELOPMENT OF THE WATER RESOURCES IN THE SOUTHERN HIGH PLAINS, NEW MEXICO

Dennis G. Woodward[79]

INTRODUCTION

The Southern High Plains (SHP) extends for 28,650 square miles in Texas and New Mexico, 5,940 square miles of which lie in eastern New Mexico in parts of Quay, Curry, Roosevelt, and Lea counties (Fig. 1). The SHP is underlain by the High Plains (Ogallala) aquifer, the source of water that enabled the development of the area. Most water on the SHP is used for agricultural irrigation; Dugan and Sharpe (1996) estimated that about 93 percent of the groundwater pumped in the New Mexico part of the SHP is used for agricultural irrigation from five main irrigation areas. From north to south they are the House area in Quay Co., the Clovis area in Curry Co., the Portales Valley area and the Causey-Lingo area in Roosevelt Co., and the Tatum-Lovington-Hobbs area in Lea County.

MANAGEMENT OF THE AQUIFER

Historically, management of the High Plains (Ogallala) aquifer in the SHP has largely been the result of differing state water laws. Under New Mexico law, all groundwater belongs to the public and is subject to state appropriation for beneficial use. Thus, groundwater management in New Mexico is the responsibility of the Office of the State Engineer (OSE). The OSE can designate groundwater basins, and a

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[79] U.S. Geological Survey, 4501 Indian School Rd. NE, Suite 200, Albuquerque, NM 87110 (e-mail: woody@usgs.gov)

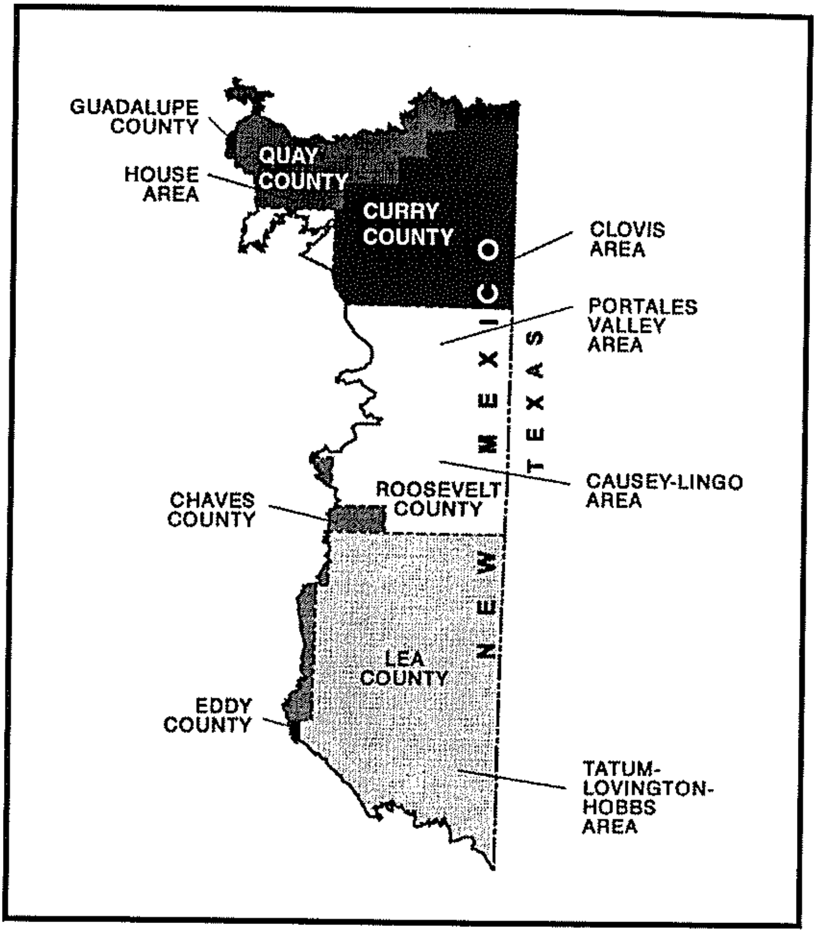

Figure 1. Extent of High Plains (Ogallala) aquifer in New Mexico.

permit is required for any groundwater used within these basins. The OSE has designated three groundwater basins in the SHP: the Lea County Shallow Water Basin (essentially the Tatum-Lovington-Hobbs area) was declared on August 21, 1931; the Portales Underground Water Basin was declared on May 1, 1950; and the Curry County Groundwater Basin (essentially the Clovis area) was declared on August 31, 1989.

Under Texas law, underlying, percolating groundwater is the property of the surface land owner. In the Texas part of the SHP, 10 local Underground Water Conservation Districts regulate the use of groundwater for irrigation.

The U.S. Geological Survey (USGS) has had an active role in assessing the groundwater resources in the SHP. The USGS does not have water-management responsibilities; its role in water resources is primarily that of data collection, interpretation, and prediction—that is, it determines groundwater pumping, monitors water-level changes, and predicts future water-level changes based on assumed pumping and recharge scenarios. C.V. Theis, one of the pioneers in American groundwater hydrology, proclaimed in an early USGS-OSE cooperative groundwater study of the Portales Valley (1934, p. 108) that "A pumping district without periodic checks on water levels and pumping would be like a bank that does not keep books."

The OSE compiles annual water-use data by county and tabulates groundwater pumpage data for the four New Mexico counties included in the SHP. In addition, the New Mexico State University Agricultural Experiment Station compiles the annual acreage irrigated by groundwater, by county, for the SHP. The USGS has the primary responsibility for compiling water-level data for the SHP.

For decades, the USGS, in cooperation with the OSE, has been collecting and publishing water-level measurements from long-term observation wells in many of the declared groundwater basins. Wilkins and Garcia (1995) provided the most recent groundwater-level change maps and hydrographs in New Mexico; the water-level change maps and hydrographs in this report were derived from their report. The USGS also collects water-level measurements from irrigation wells in the SHP each January to provide information that irrigators can use to calculate their water-depletion tax credits for the Internal Revenue Service. In addition, the Federal Omnibus Water

Resources Development Act of 1986 added Section 306 to Title III that requires the USGS in cooperation ". . . with the States of the High Plains region . . . to monitor the levels of the High Plains (Ogallala) aquifer and report annually to Congress." Congress recognized that accurate information on water-level conditions and changes is necessary to make sound management decisions concerning the use of water, to predict future economic conditions, and to conduct hydrologic research pertaining to the High Plains.

HISTORICAL DEVELOPMENT OF THE AQUIFER

Use of the High Plains aquifer began slowly. During the 1880s, several hundred shallow wells, pumped by windmills, supplied water for domestic and stock uses. By 1900, the XIT Ranch in the Texas Panhandle had 335 windmills in use (Haley, 1953). The year 1910 was pivotal in the history of water development on the SHP, but initial efforts in developing an economy based on groundwater irrigation in the area failed. The first use of groundwater for major agricultural irrigation began in 1910 in the Portales Valley when the Portales Irrigation Co. established a central electric-power plant in Portales. For a variety of reasons, the venture failed and the power plant was dismantled and sold during World War I. The first irrigation well on the SHP in Texas was drilled in 1910 a few miles west of Plainview in Hale County. The well pumped 1,700 gallons per minute, encouraging the Texas Land and Development Company to purchase several thousand acres of land and begin drilling numerous irrigation wells. Dr. Pearson, head of the company, died on the Lusitania in 1915, however, and his death slowed the development of irrigation in the area for some time (Cronin and Wells, 1960).

Agricultural irrigation using groundwater accelerated in the SHP after World War II. Acreage irrigated by groundwater in New Mexico increased from 28,000 acres in 1945, to 110,000 acres in 1950, and to a high of 350,000 acres during 1977 (Fig. 2); about 290,000 acres were

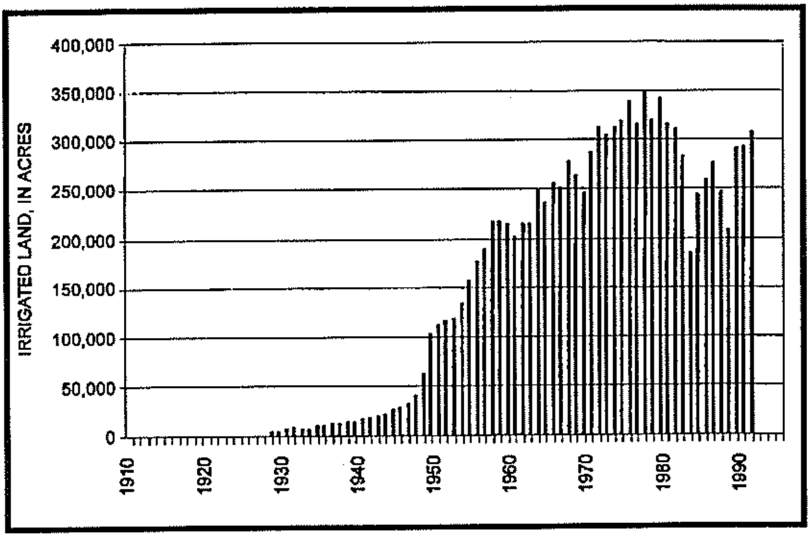

Figure 2. Trend in Irrigated acreage in the Southern High Plains, New Mexico, 1910-90.

irrigated using groundwater during 1990. Similarly, groundwater pumpage for irrigation increased from 45,000 acre-feet in 1945, to 155,000 acre-feet in 1950, and to about 650,000 acre-feet during 1970 (Fig. 3); about 670,000 acre-feet of groundwater was pumped for agricultural irrigation during 1990. The following is a brief history of the development of agricultural irrigation for each of the irrigation areas.

House Area

The House area is in southwestern Quay Co. Agricultural irrigation started in the House area during 1936; four wells supplied water to 190 acres, which gradually increased to a high of about 4,400 irrigated acres in 1950. About 3,000 acres were irrigated by about 65 wells in 1955, and 4,000 acres were irrigated in 1964. About 10,700 acre-feet of groundwater was pumped for irrigation in 1975, but this volume decreased to 4,200 acre-feet in 1985. The appreciable

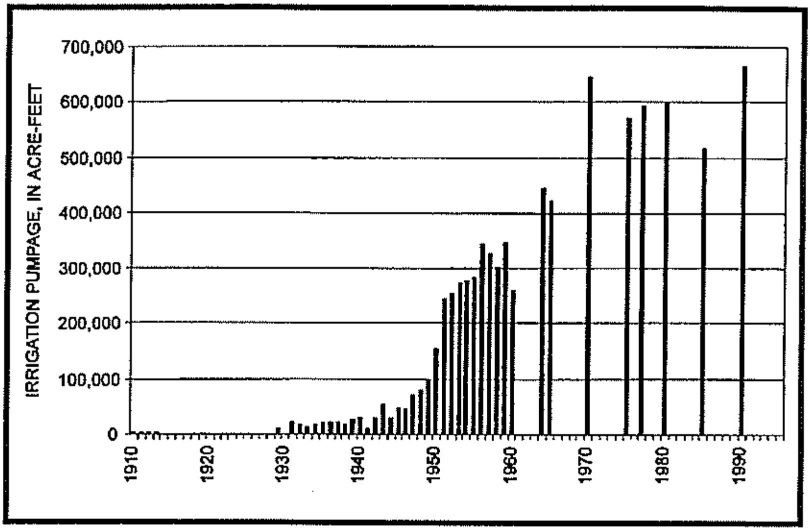

Figure 3. Trend in irrigated pumpage in the Southern High Plains, New Mexico, 1910-90 (data unavailable for some years).

groundwater-level declines prevalent in the early 1950s have diminished, and long-term hydrographs in the House area show rather constant groundwater levels since 1980 (Fig. 4).

Clovis Area

Prior to 1948, dryland farming dominated agricultural practices in the Clovis area in Curry Co. The early 1950s drought, combined with favorable economic conditions, provided incentives to increase irrigation in the area—3,500 acres in 1952, 20,000 acres from 90 wells in 1953, about 40,000 acres in 1954, about 74,000 acres in 1955, and 95,000 acres in 1960. In 1980, 255,410 acre-feet was pumped to irrigate 220,100 acres, and in 1985, 195,594 acre-feet was pumped to irrigate 111,200 acres. Irrigated acreage then decreased due to worsening economic conditions and declining water levels. The water level in a long-term observation well (well 01N.37E.15.13311) about 0.75 mile from the

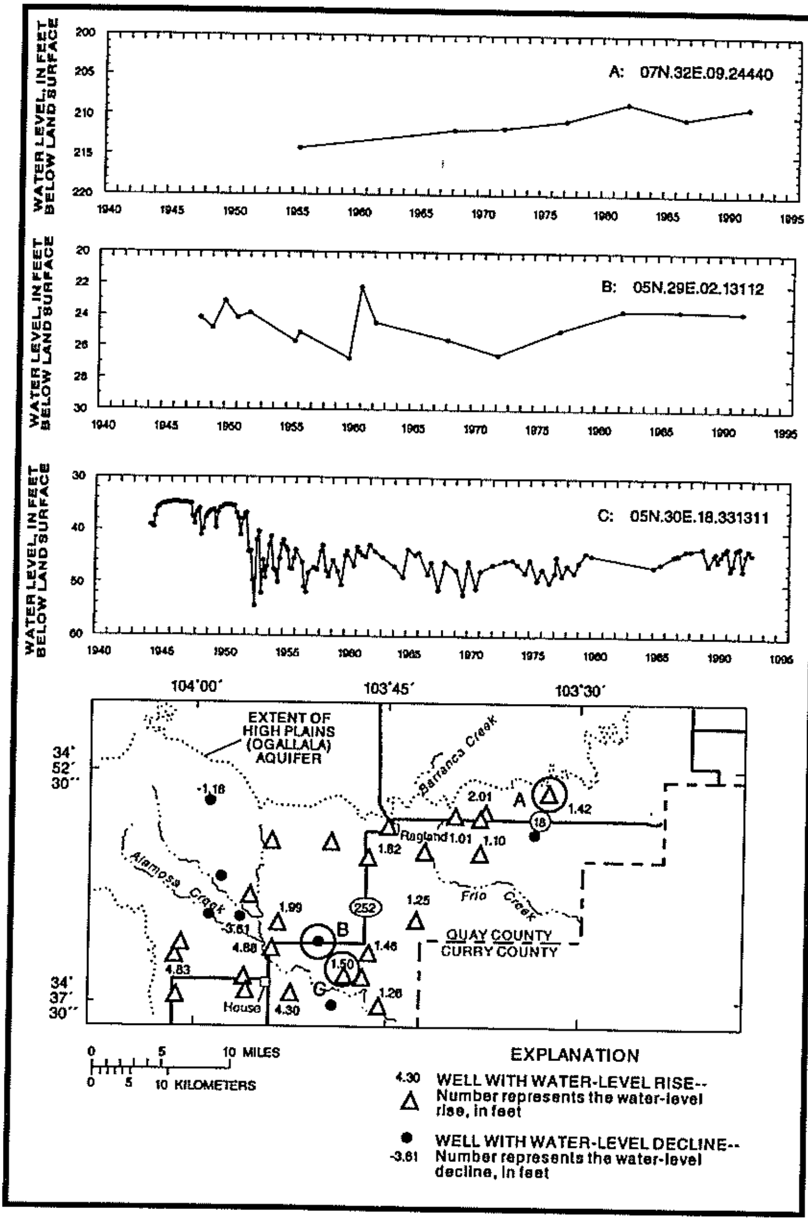

Figure 4. Long-term water levels and groundwater-level changes in selected wells in the House area in Quay County, New Mexico, 1987-92.

New Mexico-Texas state line had a 77-foot decline from 1954 to 1992 (Fig. 5). Groundwater-level declines south and east of Clovis are particularly pronounced; a number of wells showed more than 10 feet of decline from 1987 to 1992.

Portales Area

Major irrigated agriculture using groundwater began on the SHP in 1910 in the Portales Valley in Roosevelt County. Supplies came from 69 irrigation wells located throughout the valley, and about 4,000 acre-feet of water was pumped annually. Although the irrigation venture failed during World War I, irrigation began to develop again by 1925. In 1929, 166 wells were irrigating 4,823 acres, and by 1931, 300 wells were pumping about 19,000 acre-feet to irrigate 8,850 acres. Most wells had stationary or tractor engines powering centrifugal pumps. From 1910 to 1931, water levels declined 5 to 10 feet in a 26-square-mile area in the valley (Theis, 1932, p. 142); Theis recommended that the State Engineer form a groundwater district in the valley to conserve groundwater supplies. About 22,000 acre-feet of water was pumped to irrigate 11,000 acres in 1937. In 1940, about 25,800 acre-feet of water was pumped to irrigate 13,700 acres, and according to Conover and Akin (1942, p. 345), "The present irrigation development in the heavily pumped areas near Portales is probably as great as it should be for proper utilization of the groundwater supply." By 1959, about 1,200 wells were irrigating 57,650 acres, and by 1985, 95,000 acres were being irrigated. A long-term observation well (well 02S.37E.21.31212) located 1.75 miles west of the New Mexico-Texas state line had a water-level decline of 64 feet from 1954 to 1992 (Fig. 6).

Causey-Lingo Area

The first irrigation well was drilled in the Causey-Lingo area in 1945, and an intensive drilling program for irrigation wells began in 1954. By 1955, more than 80 wells were irrigating 5,000 acres. During 1960, about 8,500 acre-feet of groundwater was pumped to irrigate about

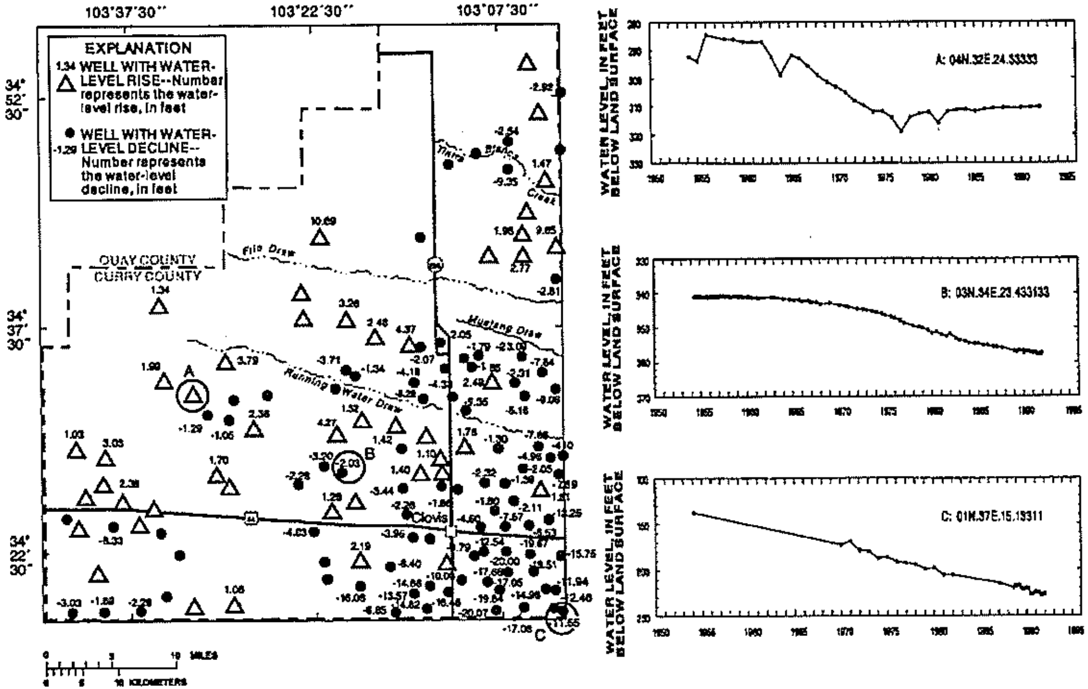

Figure 5. Long-term water levels and groundwater-level changes in selected wells in the Clovis area in Curry County, New Mexico, 1987-92.

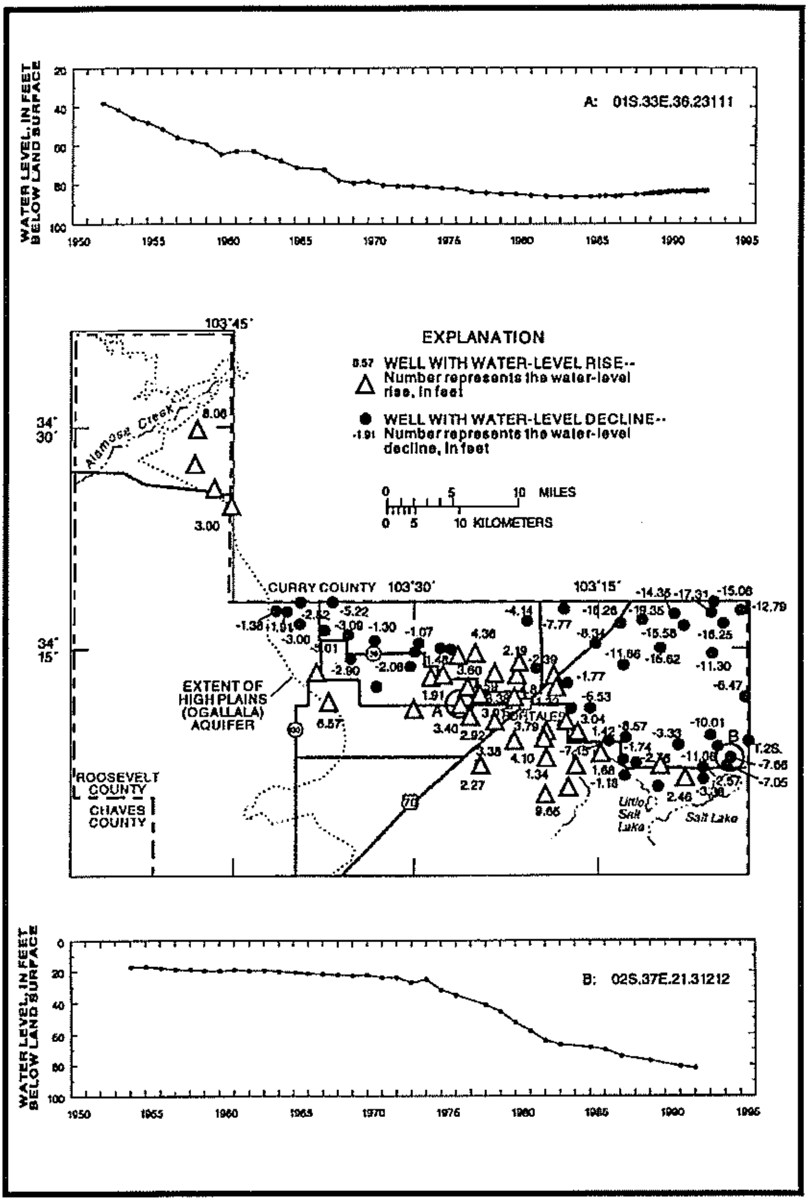

Figure 6. Long-term water levels and groundwater-level changes in selected wells in the Portales area in Roosevelt County, New Mexico, 1987-92.

6,000 acres. The USGS characterizes much of the Causey-Lingo area as an "area of little or no saturated thickness" (Dugan and Sharpe, 1996). Hydrographs for selected long-term observation wells show a gradual water-level rise in the area since 1980 (Fig. 7).

Tatum-Lovington-Hobbs area

The water table in the Tatum-Lovington-Hobbs area in eastern Lea County generally was less than 50 feet below land surface in 1930. In 1929, about 24 irrigation wells were actively pumping; during 1930, about 485 acre-feet of groundwater was pumped, and that volume increased to 1,226 acre-feet during 1933. During 1937, about 1,800 acre-feet was pumped to irrigate 1,500 acres. By 1954, about 1,000 wells were supplying 93,000 acres with irrigation. About 101,500 acres were being irrigated by groundwater by 1970. Hydrographs for selected long-term observation wells in the area show a gradual water-level decline (Fig. 8).

CONCLUSION

The SHP, underlain by the High Plains (Ogallala) aquifer, occupies 5,940 square miles of eastern New Mexico. The five main agricultural irrigation areas in the New Mexico SHP—the House area in Quay Co., the Clovis area in Curry Co., the Portales Valley area and the Causey-Lingo area in Roosevelt Co., and the Tatum-Lovington-Hobbs area in Lea Co.—use about 93 percent of the groundwater pumped.

Groundwater management in New Mexico is the responsibility of the OSE. That agency has designated three groundwater basins in the SHP that roughly correspond to the Tatum-Lovington-Hobbs, the Portales Valley, and the Clovis areas. The OSE compiles annual water-use data by county and records the groundwater pumpage used for agricultural irrigation for the four counties in the SHP. In addition, the New Mexico State University Agricultural Experiment Station compiles the annual acreage irrigated in each county. The USGS has

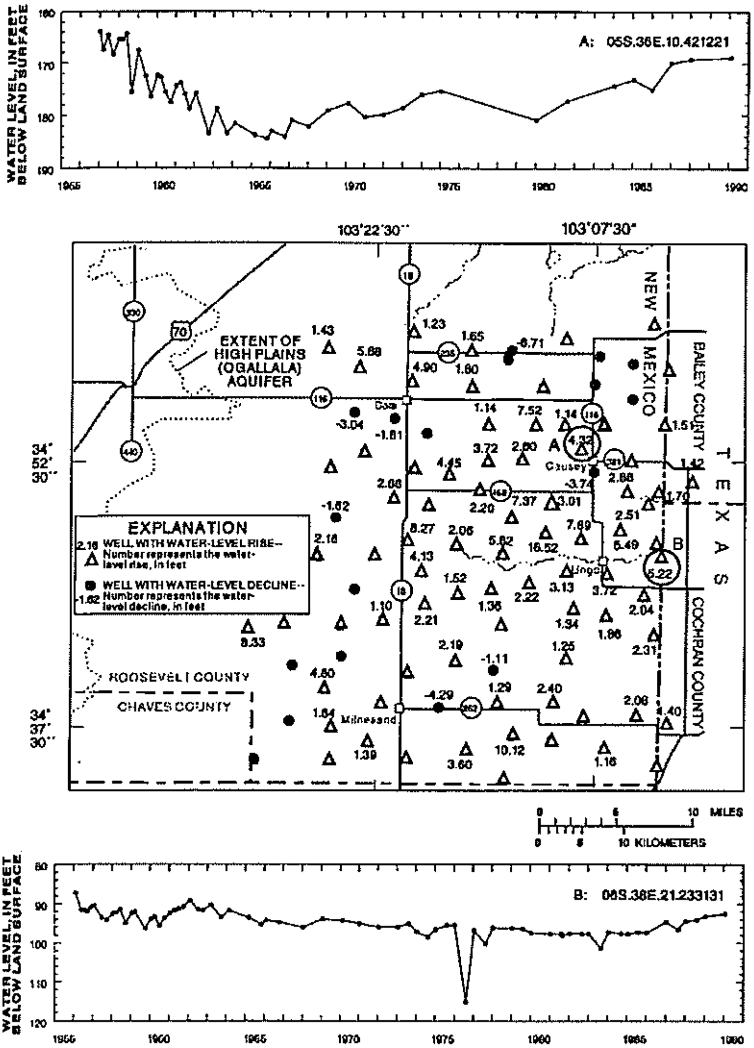

Figure 7. Long-term water levels and groundwater-level changes in selected wells in the Causey-Lingo area in Roosevelt County, New Mexico, 1987-92.

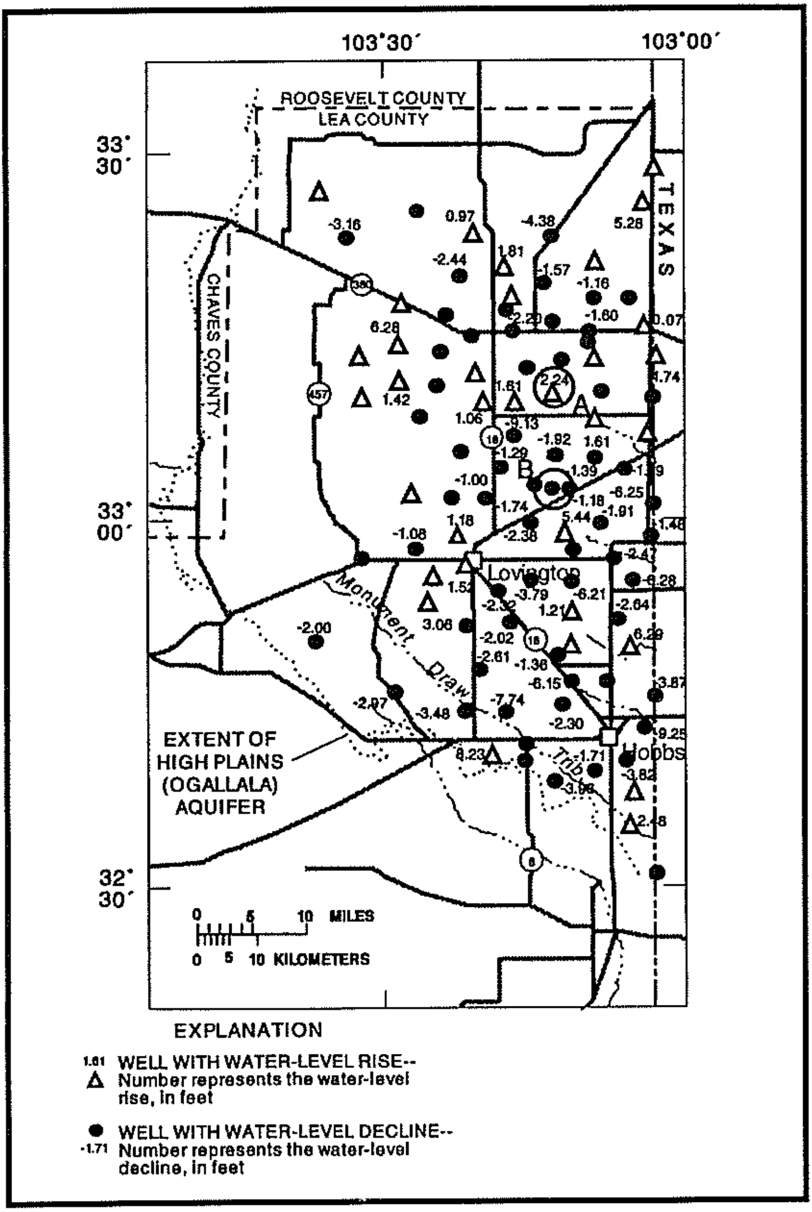

Figure 8. Long-term water levels and groundwater-level changes in selected wells in the Tatum-Lovington-Hobbs area in Lea County, New Mexico, 1987-92.

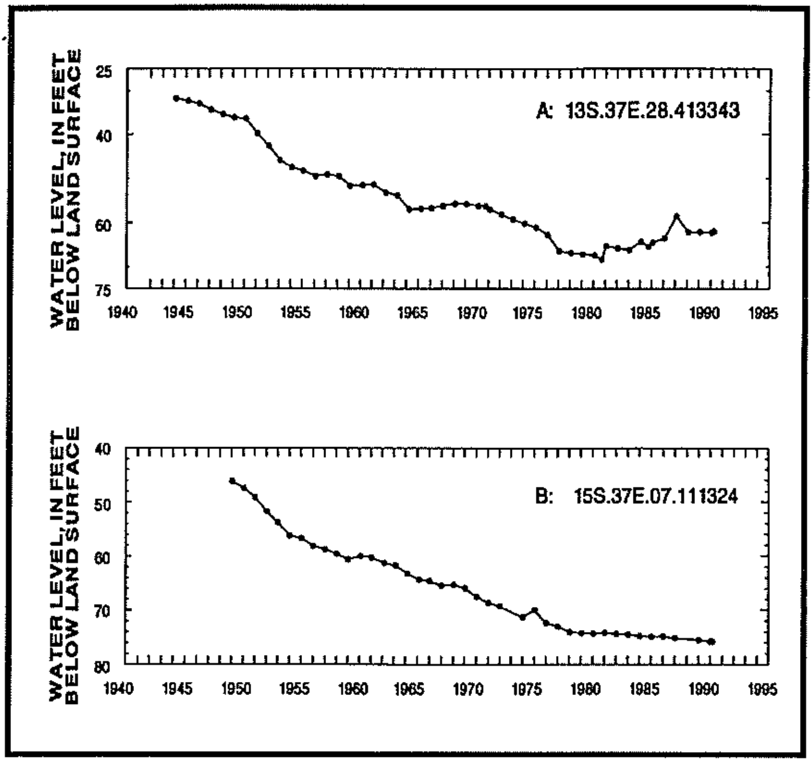

Figure 8. Continued.

the primary responsibility for compiling groundwater-level measurements for the SHP.

In the SHP, groundwater levels generally rose during 1987-92 in the House and Causey-Lingo areas. Conversely, groundwater levels generally declined during 1987-92 in the Clovis and Tatum-Lovington-Hobbs areas. In the Portales Valley area, groundwater levels rose adjacent to the town of Portales and generally declined elsewhere, particularly in the northeastern part of the area.

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AN HISTORICAL OVERVIEW OF PLAYAS AND OTHER WETLAND/ RIPARIAN AREAS OF "NUEVO MÉXICO"

Melanie Greer Deason[80]

ABSTRACT

This journal article briefly examines the history of ***Nueva España*** (New Spain) since 1541, in the context of playas and other wetland/riparian areas in the Region of ***Nuevo México*** (New Mexico). Particular attention is given to their importance and use by indigenous people, early Spanish explorers, and the subsequent settlers of *Nuevo México.* Furthermore, 1998 marks the 150th anniversary of the original signing of the Treaty of Guadalupe Hidalgo. This event is briefly presented along with several historical periods that influenced the course of water in *Nuevo México.*

INTRODUCTION

Overview of Nuevo México's Place in History

Long before European inhabitants of the United States thirteen colonies ventured west of the Mississippi River in the early 1800s, there existed a vast expanse of land called ***"Nueva España"*** (New Spain). For over three centuries (from 1519 - 1821) these lands of *Nueva España,* including the northern frontier of ***"Nuevo México"*** (New Mexico), were under Spanish rule. With independence from Spain in 1821,

Editor's Note: ***Italics*** are used to denote Spanish names given to land areas, water features, and other places of importance, including wetlands and riparian areas.

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[80] Wetlands Coordinator, Surface Water Quality Bureau, New Mexico Environment Department, Santa Fe, New Mexico 87502. (This position was partially funded by a grant from the U.S. Environmental Protection Agency, to assist Wetlands Conservation in New Mexico, Federal Assistance I.D. No. CD-996564-01-0.)

Nueva España was renamed ***"Republica de México"*** (Republic of Mexico), of which *Nuevo México* remained a part. Overall, *México's* land holdings were significant and included many states of the present day southwestern United States: New Mexico, Texas, Arizona, Nevada, Utah, most of California, half of Colorado, and portions of Wyoming, Oklahoma and Kansas. Furthermore, the Region of *Nuevo México* was larger than today's State of New Mexico, for it also encompassed the panhandle of Texas and parts of eastern Arizona, southeastern Utah, and southern Colorado. Because of the great distance between Mexico City and Santa Fe, *México* was only able to distantly rule *"Nuevo México"*. Then in 1846, at the beginning of the Mexican American War, U.S. General Stephen Watts Kearney and his military troops headquartered in Santa Fe to begin a military occupation of *Nuevo México* that would last four years. It was not until the end of this war in 1848, with the signing of the Treaty of Guadalupe Hidalgo, that the United States agreed to formally pay *México* 15 million dollars to surrender the territories of New Mexico, Arizona, California and Texas. New Mexico remained a U.S. Territory until January 6, 1912, and then formally entered the Union as the 47th State (Museum of International Folk Art, 1996; Snow, 1998).

Early Human Inhabitants of the Southern Great Plains

Prior to the Spanish and European occupation of North America, indigenous people used the playas of the plains for their livelihood. These first inhabitants are generally referred to by archaeologists as Clovis and Folsom cultures. (The terms 'Clovis' and 'Folsom' are named for the archaeological finds at the Paleoindian sites of Clovis and Folsom, New Mexico.) These inhabitants butchered a variety of large animals (megafauna) - including the elephant-like mammoth, the camel, the bison, the giant short-faced bear, and the giant armadillo. These large animals roamed the entire southern Great Plains, as evidenced by fossil-bed research sites similar to Blackwater Draw near Portales, New Mexico, and others in the upper Texas Panhandle (Murrah, 1994; Pearce, 1965; Snow, 1998). There is no doubt that these now extinct animals and their hunters used the playa wetlands of the plains as they drifted from one watering point to another. However, about seven thousand years ago, the climate of the southern plains became drier, and the mammoths and other large animals disappeared. Only the bison remained to provide food, housing, tools, and weapons for the plains residents.

When Spanish explorer Francisco Vásquez de Coronado traversed these plains in 1541, his expedition recorded the first description of playa wetlands and also named these vast prairies - the ***"Llano Estacado"*** ("Staked Plains"). Pedro de Castañeda, a chronicler of the journey, was impressed with the uniform configuration of the little lakes. He noted, *"They were round as plates, a stone's throw or more across, some fresh and some salt. The grass grows tall near these lakes; away from them, it is very short, a span or less."* Coronado found the region well-populated by both bison and Indians, and he reported that not a day passed when he did not see buffalo, although he covered nearly a thousand miles during his expeditions. The playa lakes of the high plains of northwest Texas and eastern New Mexico played a major role in making this region a breadbasket for its indigenous people - not only for those who actually lived on the plains, but also for the tribes to the west and east, who came over hundreds of miles to hunt bison, waterfowl and other wild game (Murrah, 1994).

Nuevo México and the Llano Estacado

Although the Spanish translate *"Llano Estacado"* as "Staked Plain", and *"Llano Estancado"* as "Plains of Many Ponds", some historians believe the original spelling included the 'n'. If this is true, then the translation of "many ponds" appropriately represents the playa wetlands of the Southern High Plains. Historians also believe that the early Spanish explorers of this region needed to drive stakes into the ground for tethering horses and marking trails, or that the prevalence of yucca plants on the plains may have influenced the translation to "staked plain" (Ducks Unlimited, 1991). A more literal translation of *"estacado"* is not staked but "stockaded, palisaded." This latter description is believed to be inspired by the edge of the caprock marking the *Llano Estacado's* north and west rims. If viewed from afar, these walls resemble stockade walls (Julyan, 1996).

Within the historical boundary of *Nuevo México,* lies an expanse known today as the Playa Lakes Region (of the Southern High Plains). (See Figure 1.) This region encompasses Coronado's *Llano Estacado,* and is more commonly known as the "Palisaded Plains" of Texas. From a topographic perspective, the Playa Lakes Region ignores state boundaries as it spans eastern New Mexico, the panhandle of Texas, and the smaller adjacent portions of Colorado, Kansas, and Oklahoma. Regardless, this area is the largest non-mountainous land formation

Figure 1.

in North America - an expanse of approximately 40,000 square miles - with few perennial rivers or streams, although it has nearly 22,000 playa wetlands. The *Llano Estacado* is geographically defined as the level "plains" of New Mexico and Texas that lie south of the Canadian River. In eastern New Mexico, the Canadian River is just north of the City of Tucumcari and supplies water to Ute Reservoir. Other cities and towns within the *Llano Estacado* include New Mexico's Clovis, Portales, Lovington and Hobbs; and the Texas' municipalities of Amarillo, Lubbock, Midland and Odessa (Woodward, 1994; Murrah, 1994).

EXPLORATION OF NUEVA ESPAÑA

The Spanish Named the Rivers, Waters and Wetlands

The Spanish never settled the plains areas of the *Llano Estacado,* although they did spend the next 150 years exploring the vast new regions of the southwest. During their exploration of *Nueva España,* they located and gave names to significant rivers, sources of water, and wetlands - as depicted by the numerous designations of ***"río, playa, laguna, ciénega, and bosque."*** By the 1600s, Spain began awarding land grants for their colonists to settle these new lands, under the condition that there was sufficient water to sustain crops and livestock (Murrah, 1994; Snow, 1997).

Río

Río is Spanish for "river." The ***Río Grande,*** as it is known today, originates in Colorado, travels through New Mexico and borders Texas and Mexico on its journey to the Gulf of Mexico. With its multiplicity of names from many languages and cultures, the *Río Grande* symbolizes the history of New Mexico. The oldest names in current use, given by the Pueblo Indians, usually mean the same as the present Spanish name, "big river," though Navajo mythology knows the river as "female river." When Coronado's expedition arrived in

New Mexico in 1540, his captain, Hernando de Alvarado, encountered a great river, on September 7, near the site of modern Isleta Pueblo. His party named it the ***Río de Nuestra Senora,*** "River of Our Lady," because they discovered it on the eve of the Virgin Mary's feast day. A few of the many names given to this great river that flows through New Mexico are: ***Guadalquivir*** (1581), in honor of the largest river of southern Spain; ***La Junta de los Ríos*** (1776), because of the many tributaries joining it through New Mexico; and ***Río Bravo* del Norte** (1800s), for "Bold or Rapid River of the North," which often appeared on maps although the name was not common among the people of New Mexico. In 1598, when Juan de Oñate took possession of the region of *Nuevo México* and the lands of the *Río Grande,* he announced, *"I take possession, once, twice, and thrice, and all the times I can and must, of the actual jurisdiction, civil as well as criminal, of the lands of the said Río del Norte, without exception whatsoever, with all its meadows and pasture grounds and passes."* ***Río del Norte*** is the name by which it would primarily be known for the next 250 years - this great river valley of the *Río Grande* (Pearce, 1965; Julyan, 1996).

Playa

Playa is Spanish for "beach," although in the southwest this term refers to sandy, depressed areas, sometimes lacking much vegetation, which are often dry except after intense rains when they can become a lake. In the region of the *Llano Estacado, playas* generally are intermittent (seasonal) wetlands - small, shallow, and often round or oval - usually less than 10 acres in size, though some are as large as 100 acres. *Playas* can also be saline lakes, and if this is the case, they are often a more permanent water. Studies of the *Llano Estacado* estimate that there are approximately 2,460 *playas* in eastern New Mexico and 19,340 *playas* in the Texas Panhandle. Furthermore, there are numerous *playas* outside of the Playa Lakes Region, in the more arid portions of southern New Mexico. For example, ***Playas Lake,*** west of the Little Hatchet Mountains (Hidalgo County), is 14 miles long and less than a mile wide. *Playa* wetlands can often be dry for years on end. However, when wet, they spring to life with aquatic organisms and other microscopic food sources. These sites are often used as temporary rest-stops for migratory birds; or wintering-over areas for raptors (hawks and eagles) and other waterfowl (ducks, cranes and herons). New Mexico and Texas are along the path of the Central Flyway, a route which is traveled by millions of waterfowl during their yearly migrations. (See Figure 2.) This is largely because of the important habitat that *playas*, rivers, and other wetland areas provide (Pearce, 1965; Julyan, 1996; Woodward, 1994).

FLYWAYS OF THE UNITED STATES

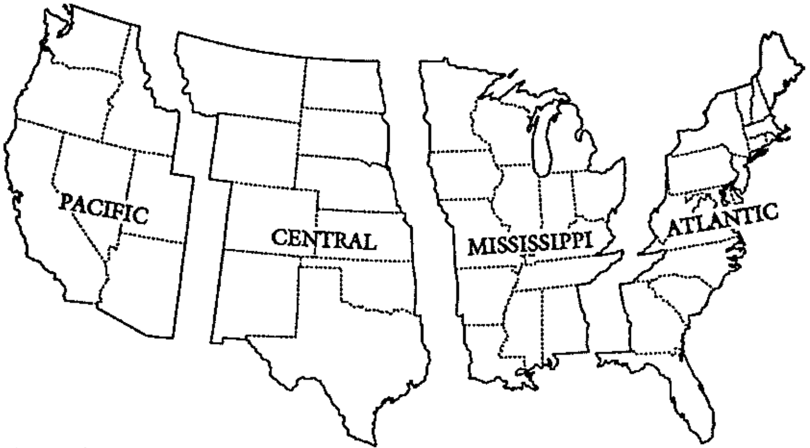

Figure 2.

Ciénega

Ciénegas are yet another wetland that the Spanish named for "marsh and marshy place," and ***Cieneguilla*** and ***Cieneguita*** are names for "little ciénega." Because a marsh would be a good source for scarce water, there were numerous New Mexico towns, creeks, and land grants named for these marshy places (Julyan, 1996; Pearce, 1965).

For example, when Santa Fe, New Mexico was founded in 1610, as the capital for this northernmost region of New Spain, it was intentionally selected because of its availability to water - the Santa Fe River. One very important requirement of Spanish land grants was that there be an adequate source of water for growing wheat and raising horses and cattle. Interestingly, when Don Diego de Vargas, Governor and Captain General of *Nuevo México,* returned to Santa Fe in 1692 (twelve years after the Pueblo Revolt of 1680) and reclaimed it for the Spanish Crown, he discovered an Indian Pueblo surrounded by a very large marsh. The L-shaped *ciénega,* located at the site of the former capital, was so extensive that de Vargas unsuccessfully requested that the Spanish Crown have the capital relocated to the opposite side of the river (Snow, 1997; Museum of International Folk Art, 1996). De Vargas wrote during his first expedition into *Nuevo México*: *"This ciénega produces mists of known and evident detriment. The Indian Pueblo is shadowed both day and night, due to heavy overgrowth of brush and trees"* (Espinosa, 1940). Immediately upon re-founding Santa Fe in 1693, de Vargas authorized ***"acequias"*** ("ditches") to be re-built for draining the *ciénega,* thereby providing water to homes and irrigation to the fields. Historically in *Nuevo México,* the first engineered *acequias* were constructed with the first Spanish settlement, also site of the first capital, at San Juan Pueblo (San Gabriel). These *acequias* were built in August 1598 due to the efforts of 1500 Indian laborers. ***"Acequia madre"*** is Spanish for "mother ditch," and symbolizes the importance of water to this region (Julyan, 1996). Even today, it is not uncommon for communities in New Mexico to have a major source of irrigation and/or drinking water provided by *acequias* (Snow, 1997; Pearce, 1965).

Laguna

Laguna is the name given by Spanish explorers to permanent "spring or stream-fed lakes." One example is the ***Laguna del Muerto*** ("Lake of the Dead Man"), more a spring-fed puddle than a lake in eastern New Mexico (Sierra County). It was the military campsite for deposed Governor Otermín in 1682 during his unsuccessful attempt to reclaim *Nuevo México* immediately after the Pueblo Revolt of 1680. This *laguna* in the ***Jornada del Muerto*** (translated as "Journey of the Dead Man" or simply "Journey of Death ") lay on the caravan routes from Chihuahua to Santa Fe. The *Jornada del Muerto* was a waterless, sandy, desolate stretch of nearly 90 miles (from Rincon to San Marcial between the San Andres Mountains and Fray Cristobal Range). Although scores of people died along its route, it was shorter by at least a day than the difficult route along the *Río Grande.* A second example is ***Laguna Pueblo,*** west of Albuquerque, whose Pueblo Indian residents were given a land grant by the King of Spain in 1689. These peoples are a Keresan group that originally named their locality *pokwindiwi onwi,* or "pueblo by the lake," as early as the 1300s. Believed to be on the *Río San José,* this *laguna* does not exist today, although the original lake bed remains as a meadow. Another *laguna,* in the western part of the state, is Zuñi Salt Lake, or ***Salina de Zuñi*** (as noted on Miera y Pacheco's 1775 map). Though owned by the Zuñi Pueblo, several tribes consider this *laguna* to be a sacred source of salt. Oñate visited the lake in 1598, and it appears in other documents by its Spanish name, ***Laguna Salada,*** or "Salty Lake" (Julyan, 1997; Pearce, 1965).

Bosque

Bosque is Spanish for "forest, woods," and in New Mexico the term has been used for dense thickets of trees and underbrush - cottonwoods, salt cedar, olive trees, willows, alders, and others - fringing lakes, rivers, streams and marshes. One example is the *Bosque del Apache National Wildlife Refuge* (Socorro County) which straddles the *Río Grande* and is located near San Antonio, New Mexico (south of Socorro). In 1845 Governor Manuel Armijo gave the ***Bosque del Apache Land Grant*** to Antonio Sandoval. This grant was later purchased by the U.S. government in 1939 as "a refuge and breeding grounds for migratory birds and other wildlife." This refuge is located on the flyways of many migratory birds and offers excellent wildlife habitat. The refuge's 57,191 acres provide sanctuary for numerous wildlife species (Julyan, 1996). Another example is the land area now occupied by Albuquerque (New Mexico's largest city), which was settled and named by Indians long before Coronado's arrival in 1540. In 1706, the Spanish governor of *Nuevo México* sent Juan Ulibarri to the area to determine its suitability for settlement. He later reported back that it was "a very good place for a new villa" and shortly thereafter, *Nuevo México's* third villa was founded (after Santa Fe and Santa Cruz). At the time of Ulibarri's visit, the locality was called ***Bosque Grande de Doña Luisa, Estancia de Doña Luisa de Trujillo, San Francisco Xavier del Bosque Grande*** and, more commonly, simply ***Bosque Grande,*** "big forest, thicket." The villa was soon named ***San Francisco de Alburquerque,*** in honor of the Duke of Albuquerque. However, by the early 1800s, English speaking travelers began dropping the first r, and the spelling eventually changed to Albuquerque (Julyan, 1996).

Riparian Wetland

Today in the southwest, including New Mexico, the riverside *bosque* is easily identified as a "riparian wetland," although many other wetlands have this riparian (land/water) relationship. Riparian areas are associated with the shores of lakes (*lagunas*); the natural and man-made banks of streams and rivers (*río, bosque*) and ditches (*acequias*); and other wetlands such as marshes (*ciénegas*), seeps and springs, and wet meadows. Since riparian zones (or riparian areas) tend to have characteristics of both the upland and aquatic ecosystem, they are transitions between: (1) the terrestrial or land ecosystem (uplands where there is seldom standing water); and (2) the aquatic or water ecosystem (where bodies of water should be common as free-flowing or standing water).

Plants growing in a riparian zone may be completely under water during a portion of the growing season, yet they may also be exposed to drought stress during other times of the year (Svejcar, 1997). Similarly, wetlands are the transitional lands between terrestrial and deepwater habitats, where the water table is usually at or near the land surface, or the land is covered by shallow water. Furthermore, wetlands are lands where water saturation is the dominant factor determining the nature of soil development and associated plant and animal communities.

Wetlands

For a site to be considered a wetland,[81] one or more of the following three characteristics must occur: wet conditions (wetland hydrology), wet soils (hydric soils), and/or wet-loving plants (hydrophytic vegetation). Therefore, it is possible for a riparian zone to be both a wetland, and a transition area between an upland and a wetland (The Watercourse, 1995; and New Mexico Environment Department, 1997). In summary, a wetland represents a relationship between land and water, which includes:

- rivers and streams (*ríos*) with their banks;
- lakes and ponds (*lagunas*) with their shores;
- springs and seeps;
- wet meadows;
- marshes and bogs (*ciénegas*);
- *playa* lakes and prairie potholes; and
- the riverside forests (*bosque*) (NM Energy and Minerals Department, 1996).

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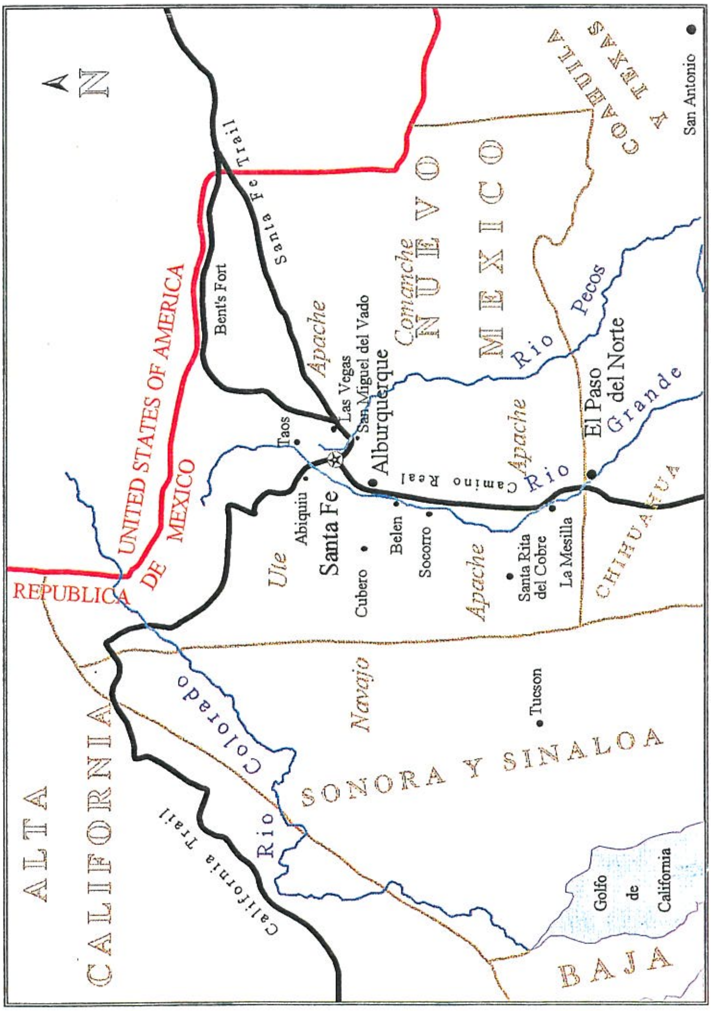
[81] Note: For Federal jurisdictional purposes, all three characteristics must be met.

Comanche Trade and the Santa Fe Trail

While the Spaniards were awed by the vastness of the plains and the abundance of the wildlife, they failed to find the objects of their quest - cities of gold. With the Comanche's invasion during the 1700s, any hopes to settle the *Llano Estacado* were lost. Nearby, in an area known today as central Texas, the Spanish abandoned their Texas frontier - settlements, ranches and missions - because of the ongoing attacks from Comanches. By contrast, in Spain's northern frontier (today's New Mexico), the Spanish succeeded in making an uneasy peace with these Indians. By the 1780s, a lively trade began that lasted nearly one hundred years. Spanish traders (known as Comancheros) annually trekked from northern New Mexico, across the presumed to be waterless *Llano Estacado,* to trade with the Comanches. In their journeys the Comancheros developed well-worn roads and utilized springs and small *playa* wetlands as water sources. They also traded blankets, guns, tobacco, and hardware for Comanche buffalo robes, meat, and slaves. In latter years, they would trade with the Comanches for cattle stolen from the early-day West Texas ranches (Murrah, 1994).

After forty years of trade between the Comanches and the Comancheros, Spanish rule ended in 1821 and *México* renamed Spain's northern province *Nuevo México.* Foreigners were now allowed to explore and trade, as the Santa Fe Trail opened for commerce between the eastern United States and Santa Fe. (See Figure 3.) This brought large numbers of Anglo and French fur trappers to hunt beaver and other fur-bearing animals in the Region of *Nuevo México.* These trappers developed an active fur trade with the East, in exchange for cotton cloth, commercial religious objects, and other manufactured items. Spanish colonists (now Mexican citizens living in *Nuevo México*) and Indians continued trading animal hides, raw wool and weavings with *México.* The Santa Fe Trail had two extensions - the original Chihuahua Trail ***(El Camino Real,*** or 'The Royal Road') to *México* and the



Mexican Independence and Trade, 1821 ~ 1846

Figure 2.

newer Spanish Trail to *Alta California* (California). The *El Camino Real* was the old and well traveled route used by indigenous people long before the Spaniards arrived; it extended from Taos and Santa Fe, south to Veracruz (on *México's* east coast). The Spanish Trail to *Nueva California* opened in 1829 and provided goods to markets on the West Coast (Museum of International Folk Art, 1996; Julyan, 1996).

The Myth of the Great American Desert

Anglo-Americans were highly uninformed about the northern region of *Nueva España.* During the early 1800s before the opening of the Santa Fe Trail, the Spanish government regarded other empires, including the United States, as "foreign" interests and prohibited trade or entry into its territories. Regardless, the United States sent its first exploring party onto the Great Plains during 1806-07. U.S. leadership was intent on fulfilling "America's Manifest Destiny" by expanding its land holding to the West Coast, including those belonging to Spain (Murrah, 1994; Snow, 1997; Museum of International Folk Art, 1996). Reports of these American expeditions were completely unlike those of the Spaniards, and created the false impression that the southern plains were a barren wasteland. Map makers soon labeled the region "The Great American Desert", with three American men largely responsible for creating this myth: Zebulon Pike, Lt. Stephen Long, and Captain Randolph B. Marcy. Zebulon Pike was the first of these Anglo-American explorers on the southern plains. In 1808 he wrote that the region would be as famous as the Sahara Desert due to its emptiness: *"Our citizens will through necessity ... leave the prairies [that are] incapable of cultivation to the wandering and uncivilized aborigines..."* Twelve years later, U.S. Army explorer Lt. Stephen Long declared emphatically that the southern plains were *"almost wholly unfit for cultivation and of course uninhabitable for people depending upon agriculture for their subsistence."*

Nearly four decades after Pike's original account, Captain Randolph B. Marcy wrote his own misunderstanding of the area, with his widely-read description in "Route from Fort Smith to Santa Fe, Letter from the Secretary of War . . . February 21, 1850": *"When we were upon the high table land, a view presented itself as boundless as the ocean. Not a tree, shrub, or any other object either animate or inanimate, relieved the dreary monotony of the prospect. It was . . . the dreaded Llano Estacado . . . a land where no man, either savage or civilized, permanently abides . . . a treeless, desolate waste of uninhabited solitude, which always has been and must continue uninhabited forever"* (Murrah, 1994). These and other erroneous reports by U.S. military expeditions would perpetuate the desert myth of the *Llano Estacado,* and temporarily buffer *Nuevo México* from Anglo-American encroachment. For instance, when Texas was annexed by the United States in 1845, its settlers soon pushed westward toward Comanche country. However, they were unaware of the extensive trade already occurring between the Comancheros and the Comanches, an alliance that would continue for another thirty years. Thousands of head of cattle would eventually be stolen from Texas ranches - destined to be butchered in the markets of Taos and Santa Fe (Weber, 1973; Murrah, 1994; Museum of International Folk Art, 1996).

END OF A LIFESTYLE, START OF A NEW

Comanche Trade Ends and the Buffalo Herds Are Slaughtered

This myth of the *Llano Estacado,* without water and impassable, persisted until 1872 when a captured Comanchero revealed to military Colonel Ranald Mackenzie that "there was plenty of water" on the plains. Mackenzie led a military scouting party across the southern *Llano Estacado* into New Mexico Territory, passing near Portales while following cart and cattle trails left by the Comancheros. It was only a matter of time before the Comanches were forcibly removed from their treasured *Llano Estacado.* Within two years, several military excursions into the region ended Comanche domination and subjected the area to rapid annihilation of the once-vast buffalo herds. Military exploration and mapping also led to the Anglo-American discovery of lakes and springs, such as eastern New Mexico's Monument Springs (Lea County) - built by Indians and named for a 45 foot high caliche-rock marker, that was visible for 35 miles. Unfortunately, in the mid-1870s the marker was torn down by buffalo hunters and used to construct a fort and corrals, which remain today (Murrah, 1994; Pearce, 1965). Overall, the playas, springs and the other wetland watering sites of the plains proved to be quite valuable to Texas cattlemen, who were ready to claim the unoccupied grass-rich prairies of the *Llano Estacado*. Especially useful were the playas, but only if the rains would keep them full. Furthermore, when this new era of cattle expansion began in the 1870s, open range began disappearing and wire fencing soon influenced an increase in land prices. By 1885 the plains were full of cattle, but unexpectedly the weather became more dry, and forced a collapse in the cattle market. With the subsequent bankruptcy of many ranching operations, most ranches disappeared. However, throughout this same period there had been a competing interest - for as early as 1879, generous land laws in the State of Texas were attracting farmers to the plains. With the agricultural revolution underway, large land companies soon subdivided the foreclosed ranches and sold to these new settlers. The region quickly filled with farmers (Acuña, 1981; Murrah, 1994).

The Land Grab in New Mexico

The Anglo-American land grab in New Mexico resembled the one that took place in Texas. However, in New Mexico the Spanish settlements were more extensive - the province of *Nuevo México* had many villages and some cities, of which Santa Fe had grown to be a trade center. Furthermore, extensive agriculture existed with a large number of families sharing in communal grants - land that was awarded during the previous centuries of Spanish rule. As members of these villages, they also acquired water rights, and rights to farm a plot of land and use the communal pasture lands and forests. However, with the end of the Mexican American War in 1848 and the signing of the Treaty of Guadalupe Hidalgo, opportunists quickly moved into the newly established New Mexico Territory to enjoy the spoils of conquest. This included controlling territorial government and administering its laws to further their own political, economic and social dominance. For example, the Santa Fe Ring amassed tremendous land holdings among its members (Snow, 1998). This new economic order also made it imperative to access funds, except that Anglo-Americans owned the banks and often charged excessive interest rates. When New Mexicans used their land as collateral and were unable to meet payments, the result was foreclosure.

The United States government also allowed speculators to initiate exploitative land and timber policies in New Mexico, which eroded the land and waterways, and hastened the demise of the small farmer. Another endeavor was the government's subsidizing of water reclamation projects - that helped the corporate agriculturists, who after the Civil War raised crops in large quantities. Unfortunately, these reclamation projects changed the balance of nature and severely impacted the *Río Grande*, as it reduced the supply of water in many areas and provided too much water elsewhere. Also, the people had no say as to where the government would build dams, and New Mexican farmers were forced to pay taxes for "improvements" whether they wanted them or not. If they could not pay for the increased taxes, their land was forfeited. The federal government also granted large concessions of land to railroad corporations and to some institutions of higher learning. By the turn of the century conservationists, concerned over industry's rape of timber and recreation lands, moved to create national forests. However, these new policies did not allow local shepherds to graze sheep on national forests without permits - that over the years increasingly favored the larger operators. As a result, New Mexicans lost two million acres of private lands and 1.7 million acres of communal lands. Today in New Mexico, the federal government owns 34 percent (34.2%) of the land, and the State owns 12 percent (11.8%) (Acuña, 1981).

THE DECLINE OF WETLANDS AND RIPARIAN AREAS

Contributing Factors

Historically, there are several factors that have advanced the decline of wetlands and riparian areas in New Mexico: overgrazing and changing fire regimes; the trapping and near extermination of beavers; and the building of the railroads. The Spanish introduced sheep, cattle and goats by the 1590s; sheep were highly valued because they could be sheared for their wool. Historical records reveal that by 1639, the missions had more sheep than Spanish colonists. By the 1700s most Pueblos also had flocks of sheep, some numbering as many as 30,000 animals (Baxter, 1987; and Snow, 1998). By the mid 1700s most of the best farmlands along the Rio Grande and major tributaries were under irrigation. Adjacent grasslands were supporting more than 135,000 head of sheep, goats, cattle, and horses, not counting those animals herded by the Navajo and Apache. Some one million sheep were being exported annually to Mexican states to the south and by the mid 1800s there were probably three million sheep in New Mexico (Scurlock, 1998). The Taos trade fairs were well-known as 'the marketplace' and continued a practice of trading - for beaver pelts, livestock hides and wool - that had occurred for centuries before the railroad. Santa Fe, as capitol of the Spanish province, was also a trade center and market. During the 1830s - 1840s, as many as 90,000 sheep were in the vicinity of Santa Fe and 100,000 sheep were in the Albuquerque area (Baxter, 1987; and Snow, 1998). When New Mexico was a U.S. territory, newspapers and livestock associations published numerous reports of overgrazing during the latter part of the 1800s. Unfortunately, there was no control over grazing on public lands in the West - the general rule was whoever got there first used the forage. One account in 1890 reported that there were 1,517,000 sheep and 210,000 cattle in the Middle and Upper Rio Grande basins (Scurlock, 1998). By 1906, unprecedented livestock numbers were herded into New Mexico, totaling 7.2 million sheep (Crenshaw, 1997).

A related factor, fire, also played a companion role in the decline of New Mexico's wetlands and riparian areas. Although natural fires became suppressed during the late 1800s, in some areas it was due to large numbers of grazing livestock, and was exacerbated by the drought of the 1890s. In contrast, human-caused wildfires increased in number and severity by 1900. Whether man-made or naturally occurring, the suppression of fires eventually became the policy of land managers. Overgrazing, in conjunction with fire suppression during the first half of the 1900s, contributed to a shift in the composition of vegetative cover - large areas of grasslands and forests became shrub lands (Crenshaw, 1997; Svejcar, 1997; Allen, 1998; and Kunkle, 1998). During the Great Depression of the 1930s, hundreds of thousands of erosion control structures were built all over the state by the Civilian Conservation Corps (CCC) - in a desperate attempt to stop erosion (Snow, 1998). However, a precursor to these events was the severe decline in beaver populations throughout New Mexico. Although beavers were once quite abundant in the mountainous, riverine and wetland areas of the southwest, they were heavily trapped by European fur trappers in the early 1800s, to be shipped to the East for hats and garment trim. Of the beavers that survived, much habitat was later lost to overgrazing, agricultural practices, and the construction of railroads. The Atchison, Topeka and Santa Fe Railroad arrived in Las Vegas, New Mexico in 1879, following the Santa Fe Trail from Topeka, Kansas; it arrived in Santa Fe on February 9, 1880 (Snow, 1998). One beaver story has been told about the east-west railroad line through Lordsburg, New Mexico: The railroad workers were laid off upon completing the tracks, so many headed north to trap beaver in the vicinity of the Gila River. There are reports that a fur trapper could easily bring out as many as 200 beaver pelts at one time (Hutchinson, 1997).

Grazing and Fire

A healthy relationship exists between grazing and fire when (1) the levels of grazing are appropriate for the amount of forage available, and (2) when natural fires are not suppressed. In this instance, desirable plants (such as grasses and forbs) continue to grow and produce healthy root systems, which hold the soils in place and retain moisture. Healthy roots are needed for plants to grow abundant above-ground vegetation, which also provide organic matter and seed sources, and lessens evaporation from the sun and wind. These relationships generate an on-going cycle that protect the land and water from erosion. Furthermore, natural fires play an important role in supporting nature's balance. When the system is in balance, conditions are created which support beneficial fires. These fires are smaller, more frequent and cooler, and they lessen the build-up of understory that would otherwise fuel hot dangerous fires. In contrast, if the landscape is overgrazed, there may not be enough desirable vegetation to keep this balance, since overgrazed sites tend to promote the invasion of undesirable brush and trees (pinyon, juniper, salt cedar, and sage brush, for example). Sites such as these become vulnerable to disastrously hot fires that can kill the remaining trees and grasses, and destroy the soil's existing seed supply. Without favorable vegetation and strong root systems, the site continues to dry out; it is unable to hold moisture and grow beneficial plants. Add periods of drought - such as occurred in the 1890s, 1930s, and 1950s - to stressed conditions in a semi-arid climate like New Mexico, and the result is land which is more susceptible to the loss of valuable topsoil (Kunkle, 1998). With poor vegetative cover, the actions of wind and water (including raindrop splash) can easily result in the formation of upland gulleys, channel erosion in rivers and streams, lowering of water tables, and even silt and sediment buildup in waterways. Eventually this series of consequences causes a chain-reaction that endangers the quality of life in and along rivers and other water sources - by polluting water for use by people (drinking and recreation), harming fish and other aquatic life (reducing the water's oxygen supply and food sources), and destroying habitat (food and cover) for wildlife and waterfowl (Deason, 1997).

The Role of the Beaver

The North American beaver is a highly misunderstood resident of riparian environments. Historically, the beaver has played a very important role in regulating watersheds on this continent, yet they were nearly exterminated by fur traders in the 1800s. It has been suggested that thousands of years of beaver activity may have created many of the West's fertile valleys - today's highly regarded agricultural lands. Prior to European settlement, estimates indicate that there were between 60 and 400 million beavers, with a density of about 10 beavers per square mile in their primary habitats (wetlands and riparian areas). However, in the 1820s, the Hudson Bay Company adopted a policy of deliberately over-trapping beavers in areas that bordered the Pacific Northwest. Their strategy was designed to discourage trappers from other countries (particularly Russia, France, and Spain) from attempting to claim territory that the Hudson Bay Company wished to control. Overall, their policy was successful - the United States eventually claimed those lands and most beavers in North America were removed from their riparian systems. Furthermore, in the newly formed Republic of Mexico, the towns of Taos and Santa Fe became regional fur centers during the 1820s and 1830s, and the nearby Sangre de Cristos were the first mountains to be stripped of their beavers. In 1897 - one hundred years ago - New Mexico's Territorial Legislature prohibited the taking of beavers, and many other states did the same (Manaster, n.d.; Svejcar, 1997).

Beaver habitat provides multiple benefits for humans and wildlife, particularly songbirds, waterfowl, aquatic insects, rodents and fish. However, once nature's engineers were removed, the dams were no longer maintained and they eventually failed. Stream energy then became confined to distinct channels that caused down-cutting and erosion, and resulted in the lowering of water tables as the deepened channels carried water downstream. In contrast, a healthy stream system spreads water across a wider path (behind the beaver dam), which allows storage of water in the flood plains, recharge of the aquifer, and lessens the damaging effects of flooding. Beaver dams also tend to slow the velocity of water and filter pollutants, by trapping sediment and excess nutrients (like carbon and nitrogen) behind the dams. In addition, when water backs up behind beaver dams, the water table rises in the riparian zone, which is important not only to the diversity of the landscape but also provides benefits for humans, plants and animals (Svejcar, 1997).

To assist recovery in the United States, some beavers were dropped by parachute into Colorado and Idaho. In 1904, beavers from Canada and Yellowstone National Park were reintroduced to the State of New York, where only ten remained at the time. By the mid-1950s, complaints started surfacing where beavers had been successfully restored. Trapping was later legalized in most areas, and today in North America, beavers are estimated to number between six and 12 million. Although beavers have been considered pests because they dam irrigation ditches and cut down trees, some landowners are selectively reintroducing beavers onto their property. Research has shown that beaver dams may improve damaged riparian areas, offer additional water storage throughout the summer and during water short years, and provide erosion and flood control (Manaster, n.d.). Simply stated, beavers are capable of repairing damaged environments, and reversing man-made mistakes and tampering - a cheap alternative to costly civil engineering projects (Hammer, 1995).

Railroads in New Mexico

While the railroads brought materials and goods that would improve the quality of life for the residents of the New Mexico territory, and provided trade connections between the east and west coasts, the railroads also damaged the land and her waterways. Railroad construction and operational practices eroded mountainous areas, streams, rivers and wetland areas throughout the southwest. Trees from nearby hillsides and mountains were clear-cut to provide both railroad ties and the railroads' path. Tracks were often located adjacent riverbeds because it was a path of least resistance and could provide easier access to water. There was also the direct filling in, damming up, or narrowing of river channels and water sources. For example, in 1886 at the Otowi siding (passing track) of the Denver and Rio Grande Railroad, the company constructed a water tank for replenishing locomotives. While developing and using this facility, a natural pool, fed by a spring, was destroyed - it was San Ildefonso Pueblo's source of sacred water from the south (Scurlock, 1998). Overall, the railroad's construction policies permanently altered the natural course of water, as loggers continued cutting wide swaths through the forests, taking trees to build the railroads and growing towns. For the next seventy years the damming of water on rivers and at springs, to store and pipe water for the trains' steam engines, would be a common practice. It continued until the 1950s, when the railroads converted to diesel fuels (Kunkle, 1998; Crenshaw, 1997).

NEW MEXICO'S CURRENT WETLANDS STATUS

Channelization and Irrigation

In New Mexico, the *Río Grande* is one of the major watercourses for the state. However, throughout this century it has been significantly channelized - from Albuquerque, New Mexico, to El Paso, Texas - to minimize flooding and to control water discharges for irrigation purposes. Associated dams controlling the release of waters are at Heron, El Vado, and Abiquiu lakes in the northern part of the state, and Elephant Butte, Caballo and Percha dams to the south. These dams have allowed urban and rural development along these waterways, which otherwise would not have been possible, and fostered water-based recreation areas in desert and high mesa ecosystems. Additionally, irrigated agriculture accounts for more than three-fourths of all water withdrawals and depletions in New Mexico's counties, although irrigated land accounts for only one-and-one-half percent (1.5%) of the state's land area (State Engineer Office, 1990). However, the process of channelization has eliminated the river's natural course and flow, which sustained much of the native vegetation in the riverside *bosques* (cottonwood willow forests). Overall, channelization has severely limited, and in most cases eliminated the water/land relationship that would normally have allowed the establishment of wetland vegetation along the river corridors which in turn supports healthy wetlands systems. Instead there are degraded banks (that result in severe soil erosion and sediment build up in rivers and reservoirs) and the loss of habitat for fisheries, waterfowl and wildlife. One striking example in New Mexico relates to the beneficial effects of natural overbank flooding, which promotes the regeneration of cottonwood trees. However, this does not occur in a channelized area when the water flow is controlled and stored behind a dam. Although the *Río Grande's* cottonwood *bosque* is the largest still-intact cottonwood forest in North America, the outcome of channelization is that these trees are mature (100 to 150 years old), and due to a lack of regeneration will most likely be the last. This represents a loss which has historically been one of New Mexico's important representations of wetlands and riparian areas (US Geological Survey, 1994).

Oil and Gas Production

Another example of the degradation of wetland areas applies to eastern New Mexico and the other four states of the Playa Lakes region. Throughout this century, *playas* have been subject to contamination from the disposal of brine and associated residues of oil and gas production. Physical causes of avian mortality from oil and salt encrustation have also been documented in close proximity to brine and oil discharges. *Playas* have been commonly subjected to the disposal of municipal sewage effluent and storm-water runoff, wastes from oil and gas production, and stockyard wastes and agricultural chemicals. Some researchers speculate that disposal into these affected *playas*, in excess of what the system can naturally process, may in part increase the likelihood of waterfowl mortality from diseases such as botulism and avian cholera. In addition to wildlife losses, researchers believe there is a serious threat of contamination to the High Plains Aquifer (Ogallala Formation) because *playa* lakes are the primary source of recharge to the underlying aquifer, providing much of the water used by residents of eastern New Mexico, the Texas panhandle, southeastern Colorado, southwestern Kansas and western Oklahoma (US Geological Survey, 1994; Davis and Hopkins, 1996).

Wetland Losses Over 200 Years

Unfortunately, with decades of misunderstanding as to their benefits, wetlands in New Mexico and nationwide have been channelized or drained and cleared, so they could be used for what were considered more productive uses: agriculture, flood control structures, stockyards and livestock production, residential and industrial development, and oil and gas production. As a result, more than one-half of the natural wetlands that existed in the contiguous 48 states have been lost since European settlement began. Today in New Mexico, wetlands cover about 482,000 acres (0.6 percent of the state's land mass), in contrast to the 720,000 acres that the US Fish and Wildlife Service estimates existed in the 1780s. This is a one-third decrease over a 200 year period. According to the U.S. Department of the Interior, the lower 48 states have lost an average of over 60 wetland acres every hour, between the 1780s and the 1980s. That is an equivalent loss of one acre per minute for a two hundred year time-span (Dahl, 1991). Recent government statistics suggest that these historic losses may be slowing. Furthermore, new initiatives, such as the Department of Agriculture's Wetlands Reserve Program, are promoting opportunities to increase wetlands acreage. Overall, the quality of our natural resources is challenged every day by efforts to balance our environmental, economic, social and political goals.

Land Status

New Mexico is the fifth largest of the fifty states, with a total area of almost one hundred twenty-two thousand (122,000) square miles. Approximately one-half of the state (44.6%) is privately owned, not counting Indian lands which comprise nearly one-tenth (9.4%) of the State. The remaining lands are owned by either the federal government (as public lands, 34.2%) or State (Trust lands, 11.8%). When compared to land size, the population total for the State is low; in 1990, it was just over 1.5 million people. However, New Mexico is the eighth fastest growing state in the nation, with a population expected to increase 33 percent and reach about two million people by the year 2005 (Babbit, 1998). New Mexico's environmentally sensitive river valleys and flood plains, which often contain shallow aquifers, will continue into the future, as they have in the past, to be the focus of population density. Albuquerque, on the *Río Grande* near the center of the State, is by far the largest city (with one-third of the State's population). The next two cities are Las Cruces, also on the *Río Grande* (near the Texas border) and Santa Fe to the north. Today, many of the indigenous people of the Pueblos remain in areas that were historically settled near wetlands and riparian areas. Furthermore, rural populations will most likely continue to utilize water courses and water sources for their agrarian livelihoods. In 1992, pasture and rangeland occupied about 82 percent of all land in the State (New Mexico Environment Department, 1997).

Conclusion

The Importance of Wetlands

New Mexico does not stand alone in its new growing awareness about the benefits of wetlands. *Playas* and riparian wetlands are only two of the many wetland areas that are becoming better understood for their vast environmental, biological and social values. Wetlands are now recognized nationwide as a valuable natural resource that provides many important benefits:

- Flood Control and Water Storage - wetlands reduce flood and storm damages by slowing storm water run-off; provide water storage during floods and slowly release it to downstream areas; and stabilize streambanks thereby reducing channel erosion.

- Water Quality and Aquifer Recharge - wetlands help improve water quality by removing sediment, nitrogen, phosphorus and other pollutants from surface water; and recharge aquifers and surface waters, ensuring that drinking and irrigation waters are available for the future.

- Wildlife Habitat and Biological Diversity - wetlands are one of the most productive ecosystems on the continent, providing principal habitat of food, water and cover for: virtually all watefowl; 35 percent of all rare and endangered animal species; fish spawning and nursery areas; and numerous invertebrates, amphibians, reptiles, and mammals.

- Recreation, Tourism, Open Space and Aesthetic Values - welands provide recreational and tourist uses for hunting, fishing, hiking, photography, etc. that not only add to New Mexico's quality of life, but also provide a significant economic gain for the state.

- Traditional Cultural and Spiritual Values - wetlands are important for Pueblo religious ceremonies - a centuries' old, uninterrupted practice that still occurs today.

- Education, Research, and Archaeological Values - wetlands provide educational opportunities for nature observation and scientific study; and offer insight into New Mexico's cultures and historical records (US Environmental Protection Agency, 1988; New Mexico Environment Department, 1997).

Wetlands - Over Twelve Thousand Years of Service to Humankind

Wetlands - as *playas* and lakes; rivers and streams; marshes, bogs and springs; and wet meadows and riparian areas - have sustained *Nuevo*

México's long historical record of human habitation. Indigenous people have inhabited this region since before the 1300s, and many of them believe they are descended from the culture of the Anasazi at Chaco Canyon. Additionally, *playa* wetlands have contributed immensely to life for both animals and humankind, as archaeological evidence suggests that humankind has lived on the plains almost continuously for twelve thousand years or more (Murrah, 1994). *Playas* not only provided water for the large, now extinct grazing animals of prehistoric times, but also attracted Indian hunters across a wide expanse to hunt buffalo. The Spaniards named the playas and most of the region's water sources, as they explored their newly claimed lands of *Nueva España* during the fourteenth and fifteenth centuries. For almost one hundred years, from the late eighteenth through most of the nineteenth century, playas and other wetlands empowered active trading between the Comanches of the *Llano Estacado* and the cultures of *Nuevo México.* Furthermore, centuries of agricultural endeavors would have been unlikely in this arid state, were it not for the floodplain lands and more permanent water sources provided by nature's wetlands and riparian areas. Likewise, the railroads arrived in New Mexico by following the Santa Fe Trail from the east - a route equally dependent upon nature's wetlands. And not to be forgotten is New Mexico's role in the Central Flyway, which serves even today as an important migratory route for millions of waterfowl.

We all benefit greatly from the land, and the animals, plants and water provided by nature's wetlands and riparian areas. These are living ecosystems that feed us and recharge water supplies; supply clean water and fertile soil; provide educational, recreational and spiritual nourishment; and even filter and process pollutants. New Mexico's heritage, its diverse cultures, and even today's lifestyles continually rely upon her wetlands and riparian resources. Water can exist without people; however, history clearly demonstrates that we cannot live without water. Therefore, an important challenge awaits us: to ensure that the remaining wetlands and riparian areas are healthy - and if necessary be protected and rehabilitated - so that they may continue to provide for New Mexico's future use and enjoyment.

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RIPARIAN MANAGEMENT ON THE BOSQUE DEL APACHE NATIONAL WILDLIFE REFUGE

J.P. Taylor and K.C. McDaniel[82]

ABSTRACT

As with many southwestern river systems, the Rio Grande's riparian zone has irreversibly changed in response to a constricted floodplain, an altered river hydrograph, and the introduction of exotic flora. In response to lost habitat, the Bosque del Apache National Wildlife Refuge is restoring riparian areas through the removal of saltcedar (*Tamarix ramosissima*) and the establishment of native vegetation. Saltcedar removal programs include mechanical control with heavy equipment and chemical control followed by prescribed fire. A flexible approach to saltcedar control is required often utilizing combinations of control methods. Revegetation involves the use of plantings on non-irrigated sites or the use of controlled flooding to mimic the historic river hydrograph. Natural regeneration occurs from the seedfall of native plants after flood waters slowly recede. Riparian restoration benefits wildlife species, saves water when saltcedar is replaced by native species, and provides recreational opportunities for the public.

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[82] Wildlife Biologist, U.S. Fish and Wildlife Service, Bosque del Apache National Wildlife Refuge, P.O. Box 1246, Socorro, New Mexico; and professor, Department of Animal and Rangeland Resources, New Mexico State University, Las Cruces, 88003

INTRODUCTION

Over the millennium, the Rio Grande's passage was dictated by natural events. Periodic flooding was a driving force in the creation and destruction of riparian plant communities. Spring flooding from the melting of mountain snows and intense summer thunderstorms moved the river back and forth across the fertile floodplain seeking easier passage. As the river cut new paths, plants and earth were swallowed by the surging water to be deposited elsewhere. Woodlands, brushlands, marshes and meadows were both destroyed and renewed by the river's action resulting in a riparian zone that supported a mosaic of plant communities with diverse faunal assemblages (Szaro 1989, Crawford et al., 1993).

The pristine nature of the Rio Grande flood plain changed irreversibly in the 20th century, however. Major irrigation developments inside and outside the river's channel began by 1914 with construction of reservoirs, conveyance canals, and drains. These developments altered the river hydrograph (Bullard and Wells, 1992) and resulted in a loss of wetland and meadow habitats (Hink and Ohmart, 1984). Changes in annual river flow patterns curtailed the natural regeneration of native trees and shrubs which evolved with the river and released seed to coincide with late spring flooding events. In this void exotic species introduced earlier this century, have flourished and now dominate much of the river flood plain.

Confinement of the Rio Grande to provide irrigation water and to prevent flooding, and a subsequent loss of riparian and wetland habitats, encouraged the U.S. Fish and Wildlife Service to establish the Bosque del Apache National Wildlife Refuge in 1939. In doing so, one of the first licenses for use of irrigation water in New Mexico was acquired to artificially apply water to sites once naturally flooded by the Rio Grande. In 1956, a license was granted to the refuge for 12,417 acre feet with a priority date of 1906, establishing it as the second granted license in the state. The beneficial use for the license is explicitly stated as "providing protection, production of food, nesting and propagation of wildlife" (Breslin and Breslin, 1995). Maintenance of the refuge irrigation system and its complex system of canals, drains, dikes, and water control structures was sporadic until 1987 due to manpower and funding constraints. In the intervening years, the water delivery system fell into disrepair and the habitats served by them deteriorated. Over the past ten years, much of the system has been rehabilitated and major improvements have been made to increase irrigation efficiency. In the absence of periodic severe flooding which set back vegetative succession and rejuvenated plant communities, needed disturbance has been accomplished mechanically through the use of heavy equipment in wetland management (Taylor, 1994), and in conjunction with saltcedar control prior to restoration with native riparian plants (Taylor and McDaniel 1998, in press). Integral to the evolution of this program has been the support of a growing public interested in wildlife oriented recreation.

STUDY AREA

The 23,162 ha Bosque del Apache NWR consists of 17,033 ha of upland mesa and desert mountain habitat. Refuge river bottomlands include 6,129 ha consisting of varying habitat types. Native woodlands are characterized by an overstory of cottonwood (*Populus fremontii*) and black willow (*Salix nigra*) with understories of coyote willow (*Salix exigua*), New Mexico olive (*Foresteira neomexicana*), saltcedar (*Tamarix ramosissima*), screwbean mesquite (*Prosopis pubescens*) and seepwillow (*Baccaris glutinosa*). Meadow areas consist of saltgrass (*Distichlis stricta*) and alkali sacaton (*Sporobolus airoides*). Exotic saltcedar has invaded much of the bottomland area since 1940 and now occurs in large monotypic tracts particularly in the southern portion of the refuge. Bottomland marshes, comprise 742 ha and are dominated by alkali bulrush (*Scirpus maritimus*), 3-square bulrush (*Scirpus americana*), hardstem bulrush (*Scripus acutus*), duck potato (*Sagitaria* spp.), and wild millet (*Echinochloa* spp.). Croplands, consisting of 461 ha of alfalfa and corn rotation, support migratory waterfowl and cranes.

The refuge supports 79 mammal species, 298 bird species, 20 fish species, and 67 species of reptiles and amphibians, many of which are dependent on native riparian habitats. Two endangered species, the southwestern willow flycatcher (*Empidonax traillii extimus*) and the Rio Grande silvery minnow (*Hyboanathus amarus*), are directly linked to native habitat declines and the expansion of saltcedar.

METHODS AND RESULTS

Restoration Planning

Riparian restoration capability is dictated by site potential and determined by manpower, equipment, and funding availability. Projects at Bosque del Apache National Wildlife Refuge are planned well in advance. Site suitability surveys have been accomplished by refuge staff in cooperation with New Mexico Institute of Technology to determine restoration potential utilizing Senator Dominici's Bosque Initiative Funding (Van Gelder and Maas 1997, Stevens 1997, Bosque del Apache NWR, unpublished data). Preliminary surveys including those which describe existing flora and topography, soil texture, soil salinity, and depth to water table are used in formulating planting prescriptions (Anderson and Ohmart 1984, Sheets et al., 1994, Taylor and McDaniel 1998 in press). Irrigation potential is also evaluated and infrastructure plans are developed for the expansion of irrigation facilities. The refuge's existing water license dictates expansion limitations and patterns of irrigation water use.

Saltcedar Control

Removal of saltcedar monocultures is necessary prior to native riparian and wetland habitat restoration. Saltcedar control can include mechanical clearing, the use of herbicides followed by prescribed fire, or more likely a combination of methods (Figure 1). Mechanical control utilizing heavy equipment, involves the removal of aerial trunks and stems followed by removal of underground root crown portions of the plant. The removal of aerial vegetation includes gathering,

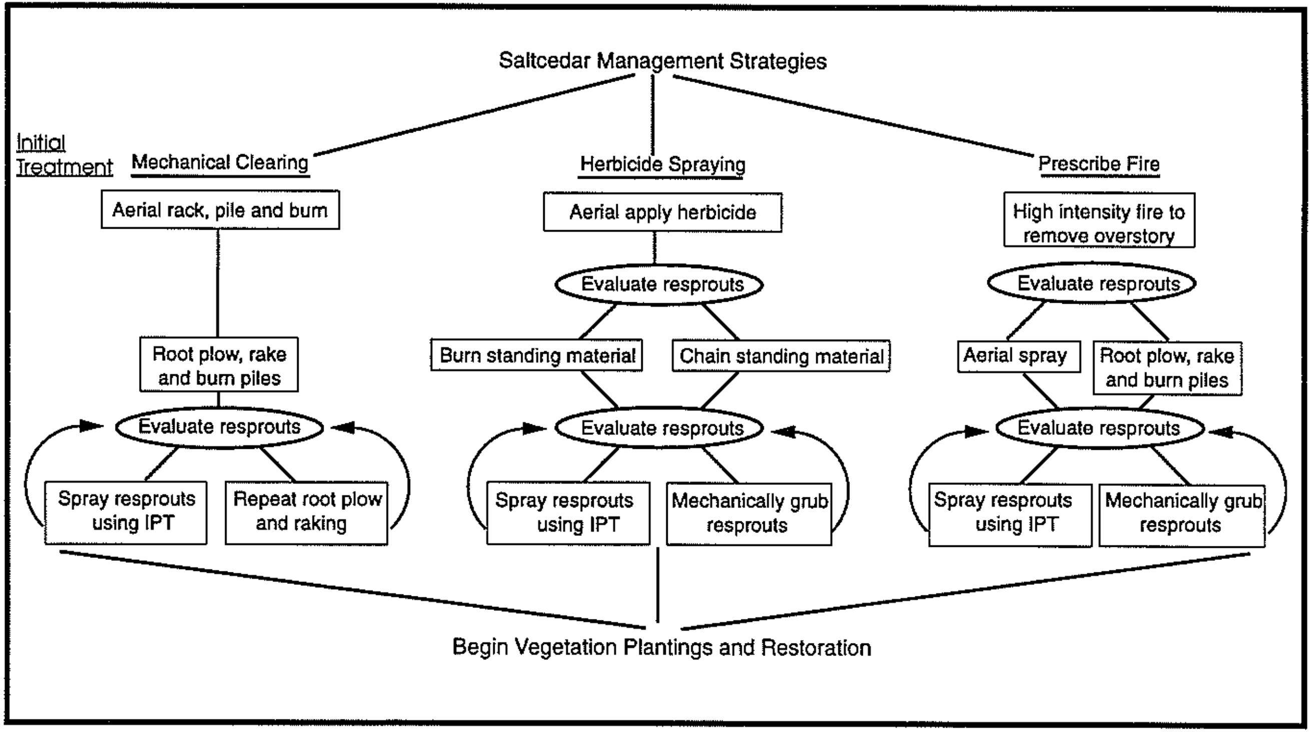

Figure 1. Saltcedar management strategies prior to revegetation.

stacking, and pile burning while the removal of underground portions includes root plowing, root raking, stacking and pile burning. Aerial vegetation removal is best accomplished during cooler winter months providing optimum working conditions for both equipment and operators. Underground vegetation removal occurs during early summer when hot and dry weather allows root crowns to desiccate. Large scale herbicide/burn saltcedar control includes aerial application of two quarts of Rodeo herbicide, two quarts of Arsenal, with a 0.25% surfactant added to the 10 gallon per acre spray solution. Foliar applications are made in early September when herbicides are quickly transported with carbohydrates via phloem tissues to the root system for storage. Follow-up individual plant treatments (IPT) using a backpack sprayer and a mixture of Rodeo plus Arsenal (0.25 + 0.25% v/v in water) during this time period aids in the control of root resprouting. Milder weather and higher relative humidity prevalent during this period leads to a reduction in the thickness of saltcedar leaf cuticles allowing easier herbicide penetration. Environmental conditions in early September also provide safer conditions for prescribed burning 2-3 years after herbicide application to remove dead aerial vegetation. Follow-up control is generally needed for at least a two-year period to treat root resprouts either mechanically or chemically. Costs for saltcedar control on the refuge have ranged from $750-$1,292/ha and generally include a two-year maintenance program (Taylor and McDaniel 1998, in press). Saltcedar plant densities have been reduced from pre-treatment averages of about 7,000 plants/ha to about 50 plants/ha 4-6 years after treatment (Table 1).

Table 1. Saltcedar Control Activities, Cost and Resulting Plant Densities on the Bosque del Apache NWR, NM

	Control Activity				
Unit	Herbicide/ Burn	Mechanical	Followup Herbicide	Cost/ha	Plants/ha
28	X	X	X	$1,030	72
29	X	X	X	$1,292	63
30		X		$750	15

Revegetation

Plantings have been widely used to restore vegetation on riparian floodplains where surface flooding for natural regeneration is not possible (Anderson and Ohmart 1982, Swenson and Mullins 1985, Fenchel et al., 1987, Taylor and McDaniel 1998 in press). Knowledge of soil texture, soil salinity and depth to water table are prerequisite to native flora revegetation projects for optimum survival and growth (Table 2). Field crews follow planting prescriptions generated from preliminary site suitability surveys. Planted materials are placed in a grid pattern, spaced 6.4 m apart. On the refuge, 120 plants are established per ha with costs ranging from \$560-\$900/ha.

Table 3. Natural Recruitment of Riparian Plants on Sites Cleared of Saltcedar Vegetation, Bosque del Apache NWR, N.M.

	Planting prescription				
Species	Soil type	Soil salinity	Depth to water table	Planting survival Unit 28	Unit 29
	(Texture	(d^{s}/m)	(m)	%	
Cottonwood	sand-loam	1-2	1.8-3.6	83	53
Black willow	sand-clay loam	1-2.5	1.2-2.4	81	87
New Mexico olive	sand-loam	1-2.5	<1.2	66	49
Wolfberry	sand-loam	3-8	<1.2	30	38
Fourwing saltbush	sand-loam	8-14	<2.0	42	0
Skunkbush summac	sand-loam	1-2.5	<1.2	30	19
Screwbean mesquite	clay loam-clay	3-8	<1.2	—[1]	40
Silver buffaloberry	loam-clay loam	1-2.5	<1.2	0	—[1]

[1] Not planted.

Two methods of plant establishment have been utilized. Dormant cuttings of cottonwood, black willow, coyote willow, seepwillow, and false indigo (*Amorpha fruticosa*) have been planted as poles from January through March over wide areas of the refuge. Poles are obtained by harvesting natural nursery stock or utilizing stock obtained from the U.S.D.A. Plant Materials Center in Los Lunas, N.M. (Fenchel et al., 1996). A 2 to 3 person work crew can cut 200 to 300 sapling tree poles per day using chainsaws. Poles are generally 3 to 7 years old and can be 2 to 5 m in length depending on water table depths at planting sites. Pole butts should be 5 to 8 cm in diameter and soaked in water for 10 days prior to planting. Holes are augered to penetrate the water table and are inserted leaving 2 to 3 apical branches above the surface on each pole (Figure 2). A two person crew using tractor mounted augers can plant and backfill 150 to 250 cottonwood and black willow tree poles per day. Tree mortality is influenced by the quality of nursery material obtained and other factors such as animal damage. Survival of cottonwoods and black willows usually exceeds 80% and growth can be rapid, averaging 0.75 m/year the first 4 years after establishment (Figure 3) (Taylor and McDaniel 1998 in press).

Propagated shrub seedlings with a minimum 20 cm of root development have also been planted on the refuge and maintained using flood irrigation. Planted species have included wolfberry (*Lycium andersonii*), New Mexico olive, silver buffaloberry (*Shepherdia argentea*), screwbean mesquite, skunkbush sumac (*Rhus trilobata*), and fourwing saltbush (*Atriplex canescens*). Prior to planting, holes are drilled to the water table and then backfilled to aid root penetration and growth. After planting, seedlings are initially hand irrigated and standard roofing felt is placed around each seedling as a weed control measure. Seedlings are flood irrigated monthly the first growing season and annually thereafter. Survival has generally been disappointing using this method and it has been discontinued in favor of natural recruitment.

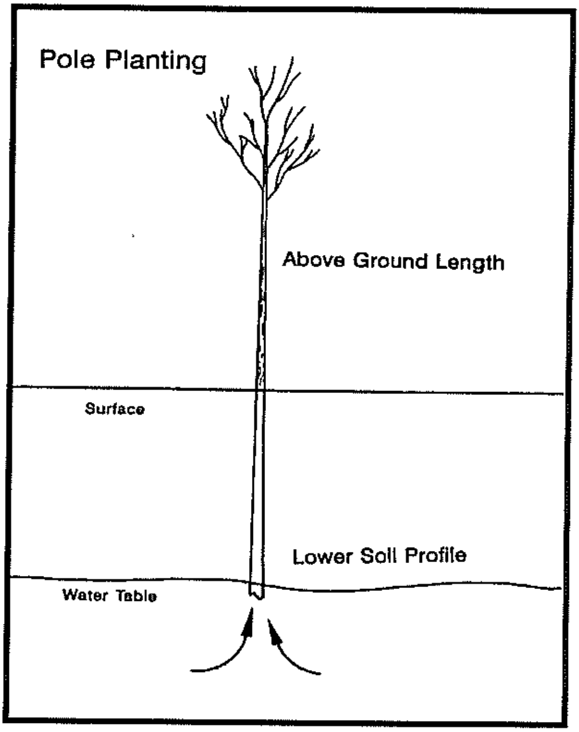

Figure 2. Dormant cottonwood poles 2 to 5 m in length are planted in augered holes that reach below the water table.

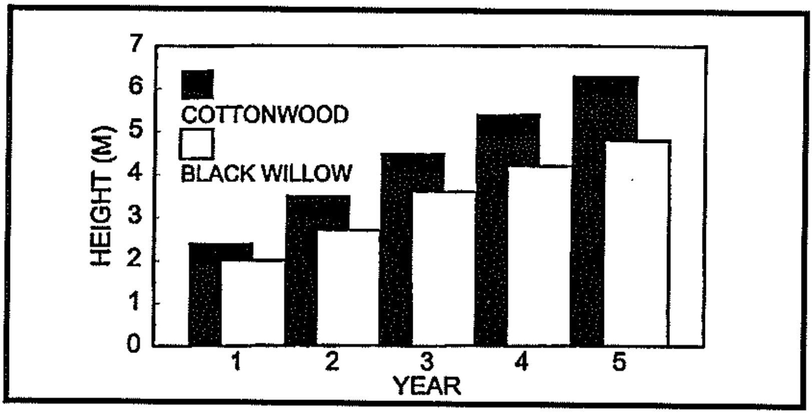

Figure 3. Average annual growth of cottonwood and black willow after planting on the Bosque del Apache NWR, Socorro, NM.

Although advances in artificial restoration using tree and shrub plantings are encouraging, some areas appear overly artificial and costs for establishment are high. The refuge now seeks to restore native woodlands or "bosques" by manipulating impounded water levels during natural seedfall periods for native riparian species. This has been accomplished using flood schedules following the historic Rio Grande hydrograph. The rate of surface water decline during seedfall, and the rate of groundwater decline thereafter dictates seedling recruitment rates and species survival on sites cleared of saltcedar.

During optimum seedfall periods on the active Rio Grande flood plain, an average 16 native seedlings and 320 saltcedar seedlings/m^2 have germinated on moist substrates exposed by declining water levels. Water table declines of about 2 cm/day can reduce saltcedar survival by 97% while native seedlings experience about 75% mortality after two growing seasons. The resulting vegetative community is dominated by robust native species which can potentially shade out saltcedar seedlings (Taylor et al., 1998 in press).

On impounded water areas outside the active river flood plain, natural recruitment has been impressive after saltcedar removal (Table 3). Although variable in the numbers and species of plants established,

Table 3. Natural Recruitment of Riparian Plants on Sites Cleared of Saltcedar Vegetation, Bosque del Apache NWR, N.M.

	Plants/ha					
Unit	**Cottonwood**	**Black Willow**	**Coyote Willow**	**Seepwillow**	**Screwbean mesquite**	**Saltcedar**
28 (7 years)	33	0	6,333	13,500	0	800
29 (6 years)	300	367	19,300	10,000	3,433	500

these areas are now dominated by healthy native plant communities. Often, water levels on large areas managed for natural regeneration can be manipulated over several years providing several age classes of vegetation adding to habitat and faunal diversity (Figure 4). Once established, subsequent flooding for the maintenance of riparian communities should occur at 5 to 7 year intervals to maintain vigorous growth.

THE FUTURE

Shortages of quality native riparian habitats coupled with growing human populations attracted to these esthetically pleasing environments are evident in the Middle Rio Grande Valley. Restored riparian areas on Bosque del Apache NWR harbor the highest diversities of avian species of any refuge habitat (Taylor and McDaniel 1998 in press). Two important avian species of concern, the southwestern willow flycatcher and the Bell's vireo (*Vireo bellii*) now utilize these areas (Bosque del Apache NWR, unpublished report). These areas have become so popular with the visiting public, a trail system has been developed to accommodate their use. Water savings can also be attributed to riparian restoration. Water consumption of saltcedar incurred through evapotranspiration and measured as the consumptive irrigation requirement, is 0.98m/year (U.S. Bureau of Reclamation, 1996) while that of cottonwood dominated vegetation on the refuge is estimated at 0.54m/yr (King and Wan, 1994). Substituting existing saltcedar with native riparian vegetation can decrease this background consumptive use. The net effect is an increase in the Rio Grande's streamflow which benefits endangered fisheries and downstream water users. Riparian restoration is therefore a win-win situation which conserves water, enhances wildlife habitat, and provides the public with a retreat from urban environments. Research will continue at the Bosque del Apache NWR to refine cost effective saltcedar control and native vegetation establishment techniques for the benefit of all interests.

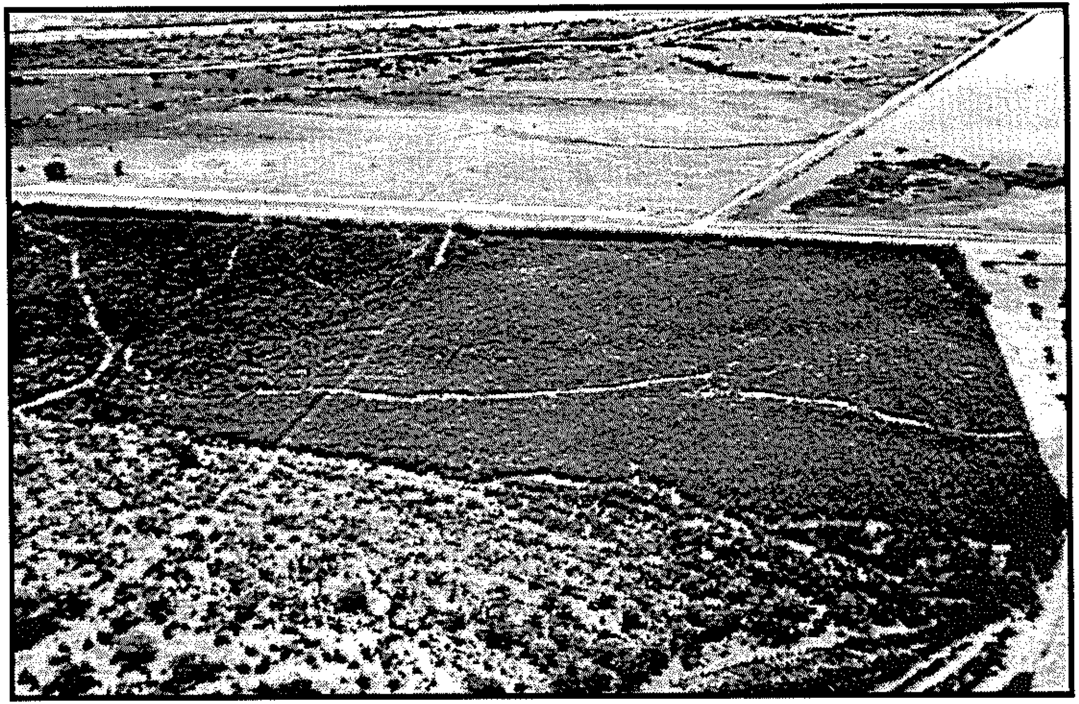

Figure 4. A homogeneous block of saltcedar (60 ha in size) was aerial sprayed with herbicide in 1987 and the standing debris was removed by fire in September 1988. Follow up mechanical work was necessary before planting trees and shrubs. This photo was taken May 1988.

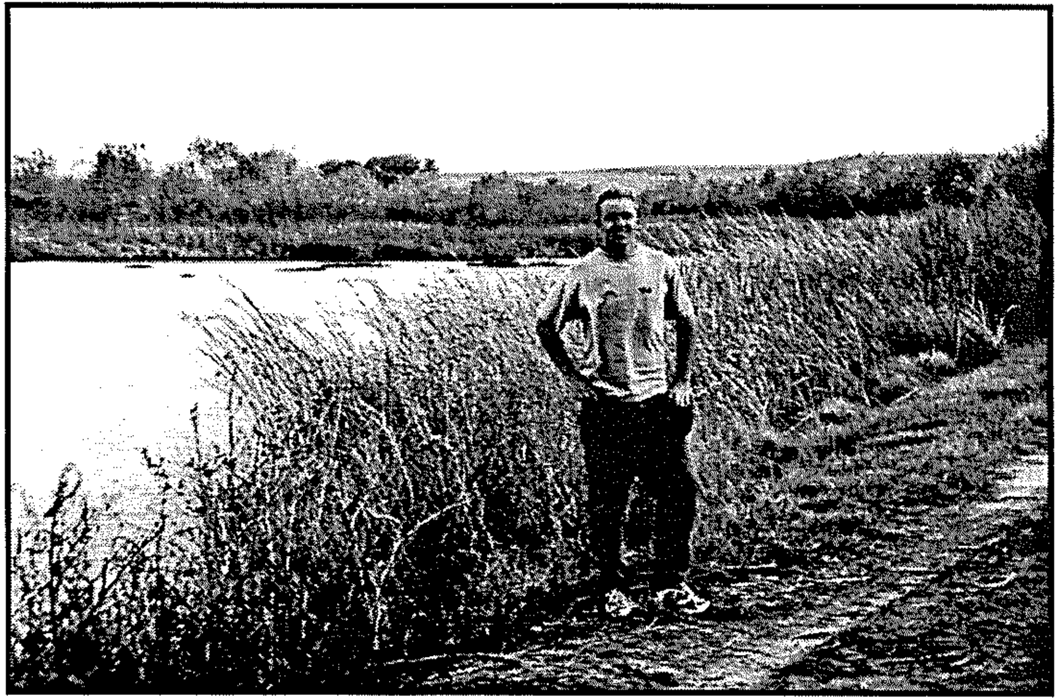

Figure 4 Continued. After saltcedar control, plantings were made and wetlands were added. When this photo was taken in November 1996, the restored area harbored the highest diversity of birds on the refuge.

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OBSERVATIONS ON SOUTHWESTERN RIPARIAN ECOSYSTEMS

Jeffery C. Whitney[83]

ABSTRACT

In order to understand the physical and biological character of southwestern riparian systems, a basic understanding of the general components of these complex and ecologically diverse systems is helpful. The natural processes in southwestern riparian systems including ecological adaptations of vegetation in response to flood induced disturbance in these arid land riparian systems is discussed. A complex set of factors are involved in the development and maintenance of these landscapes.

INTRODUCTION

The physical and biological character of southwestern riparian systems is complex. Natural processes in southwestern riparian systems and the ecological adaptations of vegetation affected by flood induced disturbance are fundamental aspects to be considered. Once understood, this relationship facilitates the ability to recognize the character and condition of the riparian reach under study both from a temporal and spatial perspective. Flood events reset the condition of these systems. Too often the casual observer interprets the effects of reforming floods as "destructive." While understandable, this conclusion may be hasty and is often incorrect.

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[83] NM Ecological Services Office, U.S. Fish and Wildlife Service, 2105 Osuna Rd. NE, Albuquerque, NM 87113

A complex set of factors are involved in the development and maintenance of these landscapes. The variability in hydrology and river morphology of these systems precludes use of random sampling in order to accurately characterize these dynamic habitats. As a result of man's activity in most southwestern watersheds today, the changes to the hydrology and the loss of active floodplain combined with changes in sediment supply and availability in the river system have all contributed to a loss of biological integrity.

The benefits of inter-annual flooding is a potential resource that was effectively used by the original floodplain and deltaic system. Development within the floodplain, accompanied by diking, alterations of the natural hydrograph, and channelizing, are the results of the perception that flooding must be controlled.

A short synopsis of both southwestern riparian ecology and the role of seasonal high flows necessary to maintain vibrant riparian communities are discussed below. The balance of the paper will be devoted to the potential for restoration of aspects of the ecological function to these highly controlled systems.

SOUTHWESTERN RIPARIAN ECOLOGY

Gregory et al., (1991) describe riparian zones, the interfaces between terrestrial and aquatic ecosystems, as a mosaic of land forms, communities, and environments within the larger landscape. These were perhaps the first authors to present an ecosystem perspective of riparian zones that focuses on the ecological linkages between terrestrial and aquatic ecosystems within the context of fluvial land forms and the geomorphic processes that create them. They observed "that geomorphic processes create a mosaic of stream channels and floodplain within the valley floor. Geomorphic and other disturbance processes of both upland and fluvial origin affect riparian zones, determining the spatial pattern and successional development of riparian vegetation."

In general, the factors affecting the development of southwestern riparian habitat are as follows:

1. creation of a favorable seedbed;
2. progression of tree stands from nursery bars to senescent individuals as they continually modify their own habitat;
3. light to moderate flooding favors the establishment and development through deposition of nutrient-rich sediments and increased soil moisture; and
4. successful seeding cannot be expected on an annual basis since it depends upon a "proper sequence of flooding," that is, no flooding large enough to be catastrophic until stands are well developed.

Stromberg (1993) found that flow volume and the related attributes of water-table recharge and floodplain soil wetting are primary factors regulating riparian vegetation abundance. For example, many riparian tree species in the arid southwest are evolutionarily adapted to germinate after high spring flows, which occur as a result of snowmelt and run-off from winter rains, whereas others germinate after high summer flows, which are driven by monsoonal summer rains (Stromberg et al., 1991). Many arid land streams are water limited on an annual or seasonal basis because discharge has such a high degree of temporal flux (Graf, 1982; Poff and Ward, 1989). The combination of high peak flows in conjunction with low mean annual flows may serve to reduce the vegetation of small streams (Stromberg and Patten, 1990). Flooding plays an important role in regulating accumulations of woody debris and nutrient dynamics in southwestern riparian ecosystems. In arid landscapes where precipitation is limited, moisture made available through fluvial interactions may play an essential role in facilitating the release of nutrients contained within wood and leaf litter on the forest floor (Ellis et al., 1995). Flood flows in some systems play a major part in 'shaping' valley floors and in physically delimiting floodplain from adjacent uplands, by variously scouring or depositing alluvial sediment (Gregory et al., 1991; Hill et al., 1991). Larger streams thus might be expected to have a greater extent of sites suitable for establishing riparian vegetation.

Flood flows of a given magnitude, frequency and seasonal timing are also important because of their roles in influencing species diversity patterns and in creating opportunities for riparian recruitment.

NATURAL FLOOD FLOW DISTURBANCE

The variability of channel morphology, flow regimes, differences in flood generated disturbances, and the intensity of those perturbations are all factors which have a direct role in the location, establishment, and relative maturity of a particular stand of riparian broadleaf trees.

Hypotheses on the coexistence of plant species (Connell, 1979), niche differentiation (Grubb, 1977), and resource partitioning (Denslow, 1980) in plant communities have relied heavily on the requirement for some form of disturbance during the life cycles of many plant species. In general, disturbance reduces the dominance of a site by established individuals and creates openings for colonization and growth by new individuals. Establishment of woody plants species associated with riverine systems in the arid southwest are no exception to these general principles.

Large volume floods are the primary disturbance event affecting southwestern riparian systems (Stromberg et al., 1991). Typically, these large flood events occur on approximately a 10-year recurrence frequency (House, 1993). In uncontrolled systems, estimating flood frequency is complicated because climate affects the magnitude and frequency of storms that cause floods (Webb and Betancourt, 1992). The magnitude of these recurring flood events is dependent upon several features including storm event, watershed condition (LaFayette and DeBano, 1990), soil saturation including snowmelt potential (House, 1993), channel morphology, and condition and associated riparian vegetation cover (Stromberg et al., 1991).

Desert streams draining large watersheds provide an excellent opportunity to test successional concepts in running waters (Fisher, 1986). The importance of hydrology to arid land riparian vegetation has long been recognized. Zimmerman (1969) stated that: "Drainage area, geology, and flow regimen are probably the three most important controls in the distribution of valley-floor vegetation" in the arid southwest. Unfortunately, all too often researchers and field personnel of various land management agencies have focused too intently upon the FORM of a given riparian area and not given substantive consideration to the FUNCTION of the area evaluated (LaFayette and DeBano, 1990).

In a generalized sense, little of what we know about lotic systems has come from work done on southwestern "desert" streams. Fisher and Minckley (1978) found that the generalized xero-riparian stream is "hydrologically flashy," responding rapidly to summer storm events with "wall of water" flash floods up to 50 cubic meters per second. The product of this and other general features of desert streams yields a stream where the main channel is wide, shaped largely by rare flooding events.

A principle effect of natural disturbance is to alter the availability of resources for plant growth. Pickett and White (1985) suggested that there are at least two mechanisms by which disturbances can temporarily increase the availability of light, water, and soil nutrients. The first is simply the reduction in rates of uptake or use of resources due to the loss of biomass. The second mechanism is the decomposition and mineralization of nutrients held in organic matter (Bormann and Likens, 1979). Large-scale disturbance as a result of out-of-bank or scouring flood flows produces a temporary increase in some of the resources necessary for the establishment of new stands of canopy species and understory plants in riparian systems in the arid southwest. In addition, there is also a net gain of energy into these systems through the movement of nutrients into the riparian zone from adjacent uplands (Meyer et al., 1988).

There is a positive relationship between disturbance size or intensity and the availability of resources for plant growth. In addition to the expected benefits of reduced biomass per unit area, the degree of reduction in rates of transpiration and interception of water, and the uptake of nutrients, there is typically a high degree of nutrient movement associated with flows of all magnitudes in riparian zones.

An important feature of any increase in resource availability produced by a disturbance is its transient nature. As biomass is reestablished at a site, the relative availability of resources for future colonists will, in general, decline. Flood disturbance produces a distinct and marked transient pulse of nutrients and organic matter into the riverine system. This represents a distinctly different pattern to which plant species can respond than that of an intact community which has equilibrated with the rate of supply of resources (Tilman, 1982). In communities where there is rapid regrowth of vegetation following a disturbance, the availability of resources for colonization should reach a peak soon after a disturbance. Consequently, the first plants that become established after a disturbance should benefit from greater availability of resources than plants that become established later. Seedlings of many species of woody plants often establish rapidly. Rapid germination following a disturbance flow should be particularly critical for species of woody plants that are intolerant of shade.

Patterns of seed production and dispersal vary widely among woody plants. One of the most conspicuous patterns of seed production and dispersal is the copious production of light, wind dispersed seed in the spring coinciding with typical spring runoff peaks. This reproductive strategy is generally correlated with the ability to respond to large disturbances (Baker, 1974). This is the case for many "pioneer" tree and shrub species which occupy recently disturbed, scoured, or deposited sediments in and along the channels of southwestern riparian systems.

There is a high degree of variability among riparian tree species to distinct geomorphological and hydrological stream habitats (Asplund, 1988). Brady et al., (1985) described the development of riparian gallery forest as beginning with moist nursery bars located in overflow channels or abandoned meanders that provide moist areas for seepwillow (Baccaris glutinosa) to pioneer. As the stand of seepwillow develops, sediment aggradation occurs providing a seed bed for cottonwood (Populus fremontii) seeds, or the expansion of Gooding willow (Salix goodingii) roots.

The high degree of variation in stand structure and composition along a given reach in desert riparian systems is an expression of a number of variables. These include but are not limited to: flow regime, substrate, elevation, seed source, timing of seed dispersal, anthropogenic activities. Therefore, it is important to take the long-term landscape (spatio-temporal) view of these systems if we are to truly understand the complex interactions of the factors contributing to the functioning of the channel and the degree to which vegetation is expressed. In addition, the associated riparian vegetation is found along the periphery of the flood channel. The broad shallow base flows meander over the sandy alluvium often is some distance away from the riparian vegetation. Where sediments are deep, flows of low discharge may occur only below the sediment surface. In these situations, surface flow only emerges where associated with underlying shallow bedrock and percolation occurs where bedrock recedes. This intermittency is a function of channel morphology and discharge. This leads to differential expression of the associated riparian communities found along the edge of the channel at bankfull flow. When sufficiently large changes between erosion and depositional processes occur, the riparian area may be unable to adjust to change, loses its equilibrium, and in extreme cases may be permanently altered and possibly damaged (LaFayette and DeBano, 1990).

There is little argument that anthropogenic activities in riparian systems and their associated watersheds have a marked negative impact upon these natural systems. The magnitude and frequency of these activities as well as the timing of the particular action have a significant role in the exhibited resulting effects. To a large extent mitigation and management can reduce these negative impacts to tolerable levels and riparian system functions may remain within the limits of acceptable natural variation.

A properly functioning riparian stream system (including the associated watershed) can be referred to as being in dynamic equilibrium. This can also be thought of as being within the acceptable limits of natural variation for that stream system. In all discussions regarding river morphology, it is important to recognize the differences within spatial and temporal scales. To describe a river system as being in a state of dynamic equilibrium (or energy balance) does not mean that it is static. To the contrary, this "equilibrium results from a collection of processes that are by definition predicated on change" through time (Crawford et al., 1993). For example, even during periods when the entire river system is considered to be in a state of dynamic equilibrium, changes constantly occur in channel segments or reaches as small as the outside bend of a meander, or as large as many river kilometers upstream, and downstream from a tributary inflow (Whitney, 1996). Likewise, this state of dynamic equilibrium, can accommodate climatic deviations from the norm distinguished between natural and human-caused perturbations. The geomorphic process triggered in response to a change in magnitude or duration of a variable, regardless of the cause, will be the same (Leopold et al., 1964).

The river constantly adjusts, always trying to establish a new equilibrium between its discharge and sediment load (Bullard and Wells, 1992).

These disturbance events remove most of the stream biota excluding native fishes, and bank vegetation. The magnitude of the flow determines the degree of regeneration and recruitment of the primary flora. Conversely, in the absence of such flows, the existing stand can become either senescent or can be overtaken by such species as salt cedar (Tamarix pentandra). Thus, one view of succession is of a temporal nature looking at conditions at intervals reset by flows of varying magnitude and frequency. In contrast, many authors have attempted to explain these systems using a Clementsian climax succession paradigm. This concept has received considerable attention and many current classification systems strive to make these riparian habitats fit some climax succession schedule. However, this has been difficult to describe adequately and impossible to predict in these disturbance driven systems. Fisher and Minckley (1978) concluded that "an ecosystem in which the entire species pool consists of 'pioneer' species is unlikely to exhibit temporal succession." The community and how the primary species are classified thus may make application of a Clementsian model awkward if not inappropriate. Sampling and extrapolating that data to fit the balance of the study area is misleading and ineffective in describing a riparian community overall due to variability of geology, valley form and substrate. It may well be that the appropriate means to measure these sites is to evaluate the species richness and the degree of maturity or size class diversity in the particular stand over time between significant disturbance flows.

LANDSCAPE SCALE ECOSYSTEM MANAGEMENT

The study of spatial and temporal patterns across landscapes is central to formulating ecosystem management principles. The hierarchical structure of ecological systems allow the characterization ecosystems and the identification of patterns and processes at different scales. Ecosystem composition, structure, and function determine diversity patterns across a range of spatial-temporal scales. There is no single correct scale at which to study and manage ecological patterns, processes, and diversity. The ecological hierarchy of interest is determined by the purpose of each project. Hierarchical monitoring schemes must be formulated that consider all scales of ecological organization. Patterns of natural variability across a range of scales must be defined if ecosystems are to be sustained at all relevant scales. Landscapes are heterogeneous mosaics of patches (Forman and Godron, 1986, Urban et al., 1987).

Programmatic riparian restoration is further complicated since rainfall and streamflow do not annually coincide with seed drop from many pioneer riparian tree species. Many arid land streams are water-limited on an annual or seasonal basis because discharge has such a high degree of temporal flux (Graf, 1982; Poff and Ward, 1989). The combination of re-organizing high peak flows in conjunction with low mean annual flows may serve to reduce the vegetative cover of (small) streams (Stromberg, 1993).

An alternative hypothesis is that geomorphological features rather than hydrological features regulate riparian abundance within a watershed. As streamflow increases, so too does the magnitude of the low frequency hydrological events. Flood flows in some systems play a major part in shaping valley floors and in physically delimiting floodplains from adjacent uplands, by variously scouring or depositing alluvial sediment (Gregory et al., 1991; Hill et al., 1991). Larger streams thus might be expected to have a greater aerial extent of sites suitable for the establishment of riparian vegetation.

Flood flows of a given magnitude, frequency and seasonal timing are also important because of their roles in influencing species diversity patterns and in creating opportunities for riparian recruitment.

NATURAL VARIABILITY IN RIVER FLOWS

Natural river systems can and should be allowed to repair and maintain themselves (Poff et al., 1997). Restoring riparian ecosystems must involve restoring or at least mimicing their natural flow regime. Realistically this will involve a mix of human-aided and natural recovery methods. Management of healthy river is more than creating an artificial constant low flow or tolerating the occasional "100-year flood" be it natural or orchestrated by man. There are five often overlooked components of a river's flow regime: magnitude, frequency, duration, timing and rate of change. Flow modification has cascading effects on the ecological integrity of rivers. The importance of natural variability to aquatic and riparian ecosystems demonstrate that unfettered rivers have multiple benefits for nature and for human society. Changes to the natural flow regime constitute one particularly important and underappreciated cause of declining health of rivers. Natural variability characterizes all ecosystems. Variability in river flow is a prime example of such natural variability. Each river has a natural flow regime, which can be altered by a variety of human actions including dams, diversions and diverse ways in which hydrologic pathways are altered. Natural variability in river flow creates a wide range of habitat types and ecosystem processes that maintain the natural biological diversity of aquatic and riparian (stream side) species. A major consequence of this natural variability is that all species experience favorable conditions at some time, preventing any one species from dominating.

Alterations of the natural flow regime result in numerous physical, chemical and biological changes to river ecosystems. Examples include not just fish migrations but recruitment of riparian trees, maintenance of sandbars in river channels, and sustenance of wetland habitat dependent upon flood plain inundation. Our understanding of the linkages between natural flow regime and the ecological functioning of rivers provides a powerful scientific basis for river management and restoration.

Letting a river do its own thing — come drought or high water — is more complicated. Most western states have recognized instream flow after some form. This may be by design or by default depending upon the river system being examined. In fact, all 11 western states have some degree of instream flow mechanisms. Despite the lack of an existing instream flow designation in New Mexico at this time, the State Attorney General and the Office of the State Engineer in April of 1998 announced that instream flow does have value for fish, wildlife, and ecological purposes. With the caveat that this would only be possible if an existing water right were employed for such purposes, it still is a positive move toward a fuller appreciation for free flowing water in riverine systems in New Mexico.

BIOLOGICAL INTEGRITY

The most influential definition of biological integrity was proposed by Frey (1975) and further described by Karr and Dudley, 1981. The concept is defined as "the capability of supporting and maintaining a balanced, integrated, adaptive community of organisms having a species composition, diversity, and functional organization comparable to that of natural habitat of the region" (Karr, 1991).

Angermeier and Karr (1994) identified two important distinctions between integrity and diversity from this definition. First, system integrity is reflected in both the biotic elements and the processes that generate and maintain those elements, whereas diversity describes only the elements. Integrity depends on processes occurring over many spatio-temporal scales, including cellular processes giving rise to genetic elements and ecosystem processes regulating the flow of energy and materials. The second distinction between integrity and diversity is that only integrity is directly associated with evolutionary context.

When a river is dammed, integrity is reduced, resulting in population declines which are adapted to the natural hydrological regime.

Integrity goals also provide for natural fluctuation in element composition. Loss of a particular element, a particular species for example, or replacement by a regionally appropriate one need not indicate a loss of integrity unless the processes associated with the element's maintenance become impaired. Biological integrity is thus generally defined as a system's ability to generate and maintain adaptive biotic elements through natural evolutionary processes. Current loss of biological integrity includes loss of diversity and breakdown in the processes necessary to generate future diversity.

ECOLOGICAL RESTORATION

The goal of ecological restoration is to produce a self-sustaining system as similar as possible to the native biota. Restoration goals must be based on social and political constraints as well as biological potential. Restoration methods usually mimic recovery from natural perturbations and reflect important organizational processes. Common approaches for aquatic systems include manipulating water quality, habitat structure, hydrology, riparian/watershed vegetation, and (less frequently) animal populations (Gore, 1985; Osborne et al., 1993). Restoration of terrestrial systems typically focuses on establishing native vegetation and manipulating succession. To maximize effectiveness, restoration efforts should employ and encourage natural ecological processes rather than technological fixes and should incorporate spatio-temporal scales large enough to maintain the full range of habitats necessary for the biota to persist under the expected disturbance regime. Riparian zones and floodplain are critical landscape components linking aquatic and terrestrial systems; they regulate aquatic habitat formation as well as movement of water, nutrients, and organic material into aquatic habitats (Gregory et al., 1991).

"Restoration" may be reasonable in many cases. In other instances, enhancement of the existing altered character of our streams and rivers may be the best we can hope to realize. Most riparian habitats are now a highly controlled or altered system with much of their ecological integrity hampered by our past or continuing activities. The thoughtful application of new understandings to the delicate and intricate balance of nature, recognition of the inevitable range of flood and drought, flexibility in management and legal applications will be necessary for improvement of the riverine habitats. The solution lies in the ability to explore collaboratively means and methods to provide the societal needs while simultaneously sustaining a healthy environment. At the present time there are a number of research, monitoring, and planning activities underway designed to contribute to the overall goal of improvement of southwestern riparian ecosystems. These activities are at all levels of government and many are collaborative efforts.

Policy effectiveness also could be improved by shifting focus from populations and species to landscapes. The organizational processes and ecological contexts that maintain populations typically operate at larger spatio-temporal scales than the populations themselves (Pickett et al., 1992). Thus management approaches focusing on strictly aquatic components (e.g., designation of a stream reach as wild and scenic or as critical habitat for an imperiled species) are unlikely to be effective over the long-term.

Dr. Hal Salwasser in 1991 made the observation that traditional agricultural, fisheries, forestry, game management, and mining agencies must replace their narrow, commodity and harvest-oriented philosophies with innovative perspectives founded on a broader range of social concerns, longer time frames, and more interagency cooperation. Critical steps toward managing for biological integrity include establishing scientifically defensible benchmarks and assessment criteria. (Angermeier and Karr, 1994). Although these steps are potentially contentious, current uses of integrity goals indicate that success is attainable.

Restoration efforts in the uplands, river corridor, in the floodplain, on public, private and tribal lands is ever increasing. We are instituting Adaptive Management in many arenas to recreate habitat which has been lost or whose quality has been severely affected by our past management activities.

The solution at first blush appears to be either too simplistic or too overwhelming. Clear understanding of what is needed, the operating space for change in administration, and recognizing that we are all part of a basin-wide community will provide opportunities to be better stewards of the finite resources we utilize.

SOCIETAL CHOICES

The causes of environmental degradation and loss of biodiversity are rooted in society's values and the ethical foundation from which values are pursued. Solutions are likely to emerge only from a deep-seeded will, not from better technology. Adopting biological integrity as a primary management goal provides a workable framework for sustainable resource use, but fostering integrity requires societal commitment well beyond government regulations and piecemeal protection. Such a commitment includes self-imposed limits of growth and resource consumption, rethinking prevailing views of land stewardship and energy use, and viewing biological conservation as essential rather than as a luxury or nuisance. The decision to conserve or exhaust biotic resources is before us. It can be informed by science and influenced by government policy, but conservation primarily depends on a societal will grounded in recognition of its obligation to the future. (Angermeier and Karr, 1994).

Quality of life does reside in a healthy environment. There are numerous economic benefits associated with vibrant, functioning ecosystems. Responsible management and administration at all levels of government and as individuals will be necessary. But without attention to these aspects, significant and perhaps irreversible consequences could result. Ultimately, the habitat we save will be our own.

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WATER CONSERVATION THROUGH AN ANASAZI GARDENING TECHNIQUE

Carleton S. White[84], David R. Dreesen, and Samuel R. Loftin

ABSTRACT

Prehistoric Native American agriculturalists practiced successful dryland farming on large areas of arid and semiarid lands in Central and Northern New Mexico. Their dryland farming techniques involved the use of gravel and/or cobbles applied as a mulch on the soil surface. Apparently, the primary function of these mulches was to reduce direct evaporation, which left more moisture available for crop growth. Successful application to current gardening and agricultural practices might significantly reduce water requirements. The field phase of this project found that Anasazi gardens were constructed on sites that had sandy upper soil horizons with either clay-rich or caliche subsoils. These gardens now are islands of native grass species and cryptogamic soil crusts within degraded grasslands. On newly constructed experimental gardens (four cobble-mulched and four unmulched, or bare), soil moisture was significantly higher on the cobble-mulch plots relative to the bare plots at every sampling except for the first soil collection three days after plot construction. Daily maximum and minimum soil temperatures were moderated throughout the year in the cobble-mulched plots relative to the bare plots. In the second year, all experimental plots were planted with a variety of crop and ornamental plants, and trees and shrubs. Each plant was watered equally during periods of limited rain to promote survival. At the time of harvest in

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[84] Department of Biology, University of New Mexico, Albuquerque, NM, 87131

early September, all the plants had higher average weight on the cobble plots than on the bare plots and the total plant harvest from the cobble plots was nearly 4 times greater than from the bare plots. Thus, cobble mulch promoted plant growth, reduced direct evaporative loss of soil moisture, and created a more moderate soil environment.

INTRODUCTION

Water is the most important single factor controlling all facets of life in arid and semiarid regions. The availability and quality of water did and will continue to influence human population growth within these regions. Despite the harsh climate, uncertainty of rainfall and the availability of water, and the temperature extremes associated with the climate of the Southwest, prehistoric Native Americans (hence referred to as Anasazi) developed agricultural crops rather than solely relying on hunting and gathering as did their more nomadic counterparts (Cordell, 1984). By the onset of the fourteenth century, the Anasazi immigrated in greater numbers into the northern Rio Grande and its tributaries from the San Juan Basin. They built multi-storied villages throughout much of the northern Rio Grande, including the lower Rio Chama, which were occupied year-round (Wendorf and Reed, 1955; Cordell, 1984). Their growing population required intensified use of the land and expansion of their agricultural production. From the early fourteenth century into the early fifteenth, cobble-mulch gardening, in combination with other techniques, allowed ancient farmers to cultivate areas previously considered unsuitable for agriculture (Lightfoot, 1993, and 1994).

The systematic use of a variety of water harvesting and conservation techniques ensured that even marginally available water was not wasted. Anasazi farmers of the Rio Chama created a protective mulch by placing materials at hand, either pebbles, gravels and/or cobbles, as a layer on the soil surface (various terms are applied to these rock-mulch features depending on size; pebble, gravel, or cobble mulch). Larger cobbles were used to outline a grid within which a mulch of smaller stones or gravels were placed (Lightfoot, 1993). The use of these structures as gardens has been confirmed by the repeated recovery of maize and native cotton pollen in soil samples, and from the discovery of stone cultivation tools on mulched gardens (Anschuetz et al., 1985; Lightfoot, 1993, and 1994). The garden plots covered hundreds of hectares of terrace and mesa tops around Anasazi pueblo sites.

Where lithic-mulch agriculture was used by indigenous cultures, it was used in warm, arid regions that experience growing-season moisture deficits. Lightfoot (1994) noted that cobble- or pebble-mulch agricultural techniques arose independently in many cultures and have been used for over 2,000 years. Roman agriculturalists used stone mounds to cultivate grapes and olives between 100 B.C. and 400 A.D. The Maori people of New Zealand utilized cobble-mulch gardens from 1200-1800 A.D. Ash mulch from a volcanic eruption in 1740 has been used by natives of Lazarote in the Canary Islands to grow a variety of fruits and vegetables. People in central China have used cobble-mulch fields to grow fruits, vegetables, and cotton for two centuries. These early agriculturalists were obviously aware of the hydrological advantages of cobble-mulch techniques.

The primary function of the cobble-mulch technique appears to be the reduction in water lost by direct evaporation, but rock mulches may have beneficial effects on soil temperature, at least in some regions. Cordell (1984) claimed that gravel-mulched gardens in the Rio Chama valley in Northern New Mexico stabilized soil temperatures (moderated temperature fluctuations) and increased overall soil temperature, which extended the growing season beyond the typical 86 to 134 days for that area. About 90 km to the southeast in the Galisteo Basin, Lightfoot (1994) suggested that pebble-mulch was used to increase soil temperatures, which promoted germination and growth of crops and extended the growing season. However, what we "know" about cobble-mulch gardens is founded upon observations from a limited number of sites with gardens in their present condition (Cordell, 1984; Lightfoot, 1994), and from a limited number of excavated gardens (Anschuetz et al., 1985). There are no empirical data that test hypotheses about the structure and function of these gardens.

This project tests hypotheses about the structure and function of cobble-mulch gardens. This was a multi-year, 2-phase investigation into the physical structure and hydrologic and thermodynamic properties of cobble-mulch gardens. Phase 1 was a field investigation of three Anasazi cobble-mulch gardens near Ojo Caliente, NM (Figure 1). The objectives of Phase 1 were: (i) to determine if soils from different gardens had similar properties; (ii) to determine if soil fertility was depleted within the garden plots; and (iii) to identify differences in vegetative cover between cobbled and uncobbled sites. Phase 2 involved an empirical test of the effects of cobble on hydrologic, thermodynamic, and plant production characteristics of newly constructed

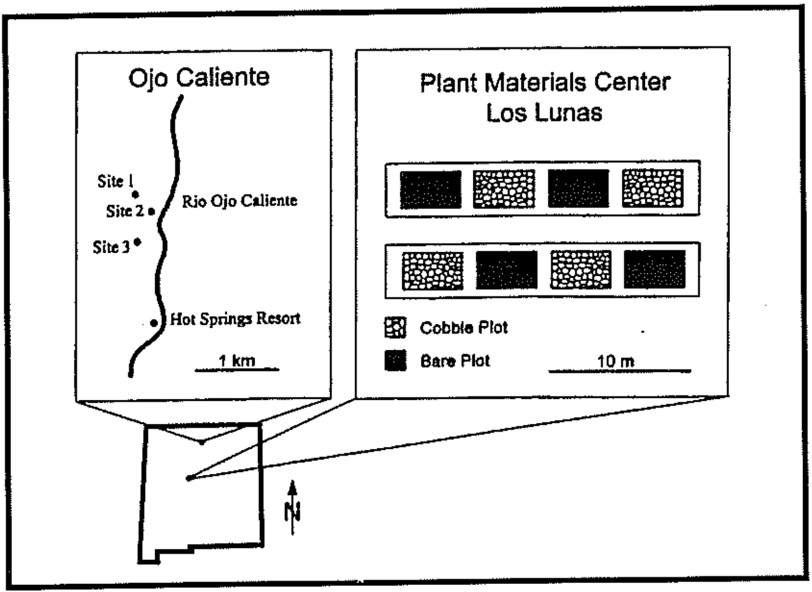

Figure 1. Drawing indicating the approximate location of the study sites at Ojo Caliente and the experimental gardens at the Plant Materials Center.

experimental gardens, which were based on soil characteristics identified in Phase 1. The objectives of Phase 2 addressed three questions. (i) When water inputs are equal (precipitation only in the first year, or minimal irrigation in the second year), do cobble plots retain more soil moisture relative to bare plots? (ii) What effects do cobbles have on soil temperatures? (iii) Given the same, yet limiting, amount of water inputs, do plants grow better on cobble plots relative to bare plots?

METHODS

Phase 1

This field investigation surveyed Anasazi gardens in different topographic locations to identify features that are common to different gardens; however, it was not a rigorous statistical test of the current garden conditions. With the aid of Paul Williams (Bureau of Land Management, Taos office), three gardens were chosen that were relatively undisturbed by domesticated animals. The gardens are approximately 1 to 1.5 km north of the Ojo Caliente Hot Springs Resort (Figure 1). The gardens occur on Pleistocene fluvial gravel terraces that are west of the Rio Ojo Caliente (May, 1979). There is little slope to all the gardens. The northern-most garden (Site 1) was on the highest of the two alluvial terraces above the Rio Ojo Caliente. The middle garden (Site 2) was on the first terrace below the alluvial terrace with Site 1. The southern-most garden (Site 3) also was on the first terrace, but it was at the base of a hill composed of precambrian metarhyolite and gneissic granite (May, 1979).

Soil Sampling and Analyses

A total of six soil samples were collected along a single soil transect at each site using a 76 mm diameter tube (sample design pictured in Figure 2). Two samples at each site of the 0-10 cm depth surface soil horizon (A horizon, if present to that depth) were collected from outside of the garden at 0.5 m and 1 m from the border. At 0.5 m and 1 m from the border within each garden, the cobbles and gravel were removed from the surface and soil from between the cobbles within an approximate 8 cm diameter area (about the size of the collection tube) was collected and combined with the 10 cm-depth sample of the underlying A horizon. The surface of the B horizon within the garden was then exposed and samples of the top 10 cm of the B horizon were collected approximately 0.5 and 1 m from the border.

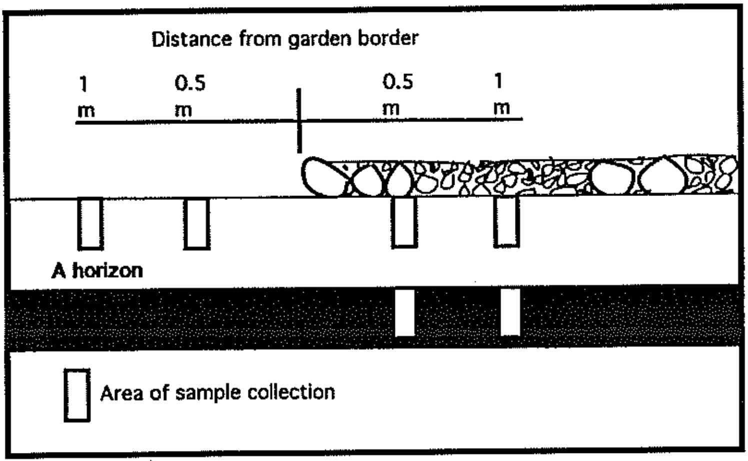

Figure 2. Schematic showing the approximate location of soil samples for assessment of fertility and characteristics of Anasazi gardens near Ojo Caliente.

All samples were placed on ice and transported to the laboratory for analyses. The samples were sieved and the portion that passed the 2 mm sieve was retained for analyses. Field water content was determined by loss-upon-drying at 105° C for 24 hrs. Particle-size (percent sand, silt, and clay) was determined by the hydrometer method (Day, 1965). Organic matter was determined on the oven-dried sample by loss-upon-ignition at 500° C. Water holding capacity (WHC) was determined by first saturating a portion of each sample contained in a funnel with water, then allowing the sample to drain by gravity for 30 minutes. The amount of water retained by the sample was determined gravimetrically by drying the drained sample at 105 °C for 24 hr. Soil fertility was assessed by measurement of potentially mineralizable nitrogen (White and McDonnell, 1988). This method measures the amount of inorganic nitrogen (N, in the forms of ammonium and nitrate) able to be extracted from the soil and liberated over a given incubation period. Asymptotic production of inorganic N is reported as 'mineralizable N,' which is directly proportional to soil fertility.

Soil Temperature

In July of 1994, four temperature probes were installed at Site 1 (upper-most terrace) at 2 and 20 cm depths both inside and outside the plot and connected to a data logger. The data logger was checked monthly; however, damage to a probe prior to a visit on September 10, 1994, caused a short or grounding of the circuit and all data prior to that visit were lost. Only three soil probes were operational after that date.

On September 10, 1994, temperature probes with data loggers (HOBO™, Onset Instruments, Pocasset, MA) were installed approximately 1 m above the ground at Site 1 (on the highest terrace), at Site 2 (on the lowest terrace), at the base of the terraces in the river floodplain below Site 2, and at about 100 m east of the Rio Ojo Caliente (one at each location). The data loggers were set to collect data for 30 days, taking one reading every 24 min. The data loggers and probes were removed on Oct. 8, 1994, at which time it was noticed that the probe at Site 1 had been cut (on Sept. 24, according to the data).

Vegetation Sampling

Ground cover and plant cover were determined using line-intercept transects (one transect per plot). Ground cover and plant cover were recorded as they intercepted the plane perpendicular to the ground as defined by the edge of the tape. Intercepts were recorded to 1.0 cm accuracy. Since some plants overshadow the soil surface, some locations have both plant and ground cover, so total cover may exceed 100%.

Phase 2

Experimental cobble-mulch gardens were established at the Plant Materials Center in Los Lunas, NM. The experiment contained four cobble-mulched gardens and four bare, control plots. The garden plots were constructed by first mechanically removing the existing vegetation and approximate leveling of the site. Two trenches, approximately 4 m wide by 24 m long, were excavated to a depth of about 30 cm. A layer of a clay loam soil was laid in the bottom of the trench and compacted with a tractor, resulting in about a 3-cm thick layer. The purpose of this layer was to impede the downward movement of water, which mimics the function of similar features found in excavated cobble gardens during Phase 1. The trenches were filled with original topsoil to a depth of about 30 cm. Alternating cobbled and bare gardens, two each overlying each trench, were constructed (Figure 1). Each garden measured 3 by 4 m with a 1 m walkway between and at the end of each row of gardens. At the center of each plot, temperature probes with data loggers (HOBO™) were set at 5 cm depth beneath the original soil surface. Construction of the plots was finished in February, 1995.

During the first year following establishment of the cobbled and control plots, all plots received only direct precipitation. All plots were weeded manually as needed to minimize transpirational loss of soil moisture. Soil temperatures were periodically downloaded from the data loggers during the course of the study. Climatic data were provided from the weather station at the Plant Materials Center, which is about 300 m from the experimental plots. Soil samples were collected with a 2-cm diameter corer to a depth of 15 cm to avoid damaging the compacted clay loam. At each sampling, four cores were taken from each plot to obtain representative coverage, composited, and analyzed for moisture content. Four additional cores were taken from each plot at the beginning of the experiment and composited for soil texture and other initial soil characterizations. Soil samples were transported to the laboratory, where they were sieved and the portion passing the 2-mm sieve was retained for analyses. Field water content was determined by loss-upon-drying at 105° C for 24 hrs. Total nitrogen and phosphorus was determined by Kjeldahl digestion (Schuman et al., 1973), followed by analyses on a Technicon Autoanalyzer (White, 1986). Water holding capacity, particle size, and mineralizable N were determined as described above.

All gardens (cobbled and bare) were planted with a variety of crop plants, ornamental perennials, and shrubs starting on June 26, 1996 (Figure 3). The same planting pattern was used for the four cobbled and four bare garden plots. The plants included two rows of native Hopi corn (ten plants), two Hopi squash plants, two Hopi bean plants, and one each of a number of potential landscape plants (see Table 5 for common and scientific names). The plants and vegetables exhibit a wide range of watering requirements from low to high water use (City of Albuquerque, Plant List).

All plants were grown from seed at the Plant Materials Center and transplanted to the gardens on June 26, 1996, except Giant Sacaton and Indian Ricegrass, which were planted a few days later. One thousand ml of water was added to the soil around each seedling after planting. Throughout the summer, each plant was watered equally, regardless of its water-use or whether it was in a cobbled or bare plot. Within the first two weeks, plants that died or fared poorly were replaced. After the first two weeks, plants that died were left in place, but still were watered. If it did not rain and the plants showed signs of water-stress, a maximum of 500 ml water per week was given to all plants (or the equivalent of 0.3 cm of rain over the entire plot per week). Thus, all plots received the same amount of water at all times, regardless of the number of live plants.

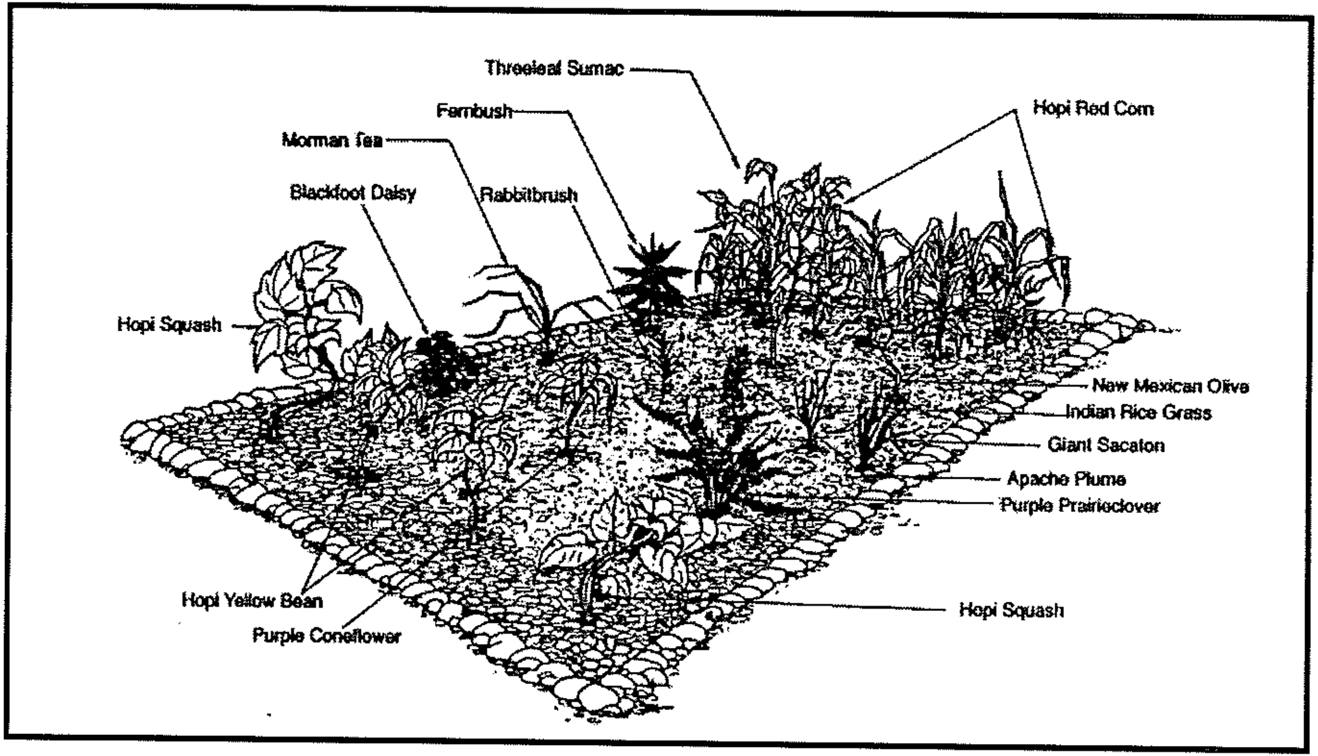

Figure 3. Drawing of experimental cobble garden indicating the placement and types of plants.

All plots were weeded to retain all soil water for the growth of the experimental plants only. At two times in early August, an insecticidal soap solution was sprayed on the squash plants to reduce aphid attack. No fertilizer or other pesticides were used in this experiment.

All plants, live or dead, were harvested on September 11, 1996. The above-ground portions were removed at the ground or about 5 cm above the ground for the woody perennial trees and shrubs. The plants were taken to the laboratory at the University of New Mexico and weighed (wet weight). The plants were cut into about 10 cm sections to decrease drying time and were dried in a forced-air oven (60⌋ C) until they reached a stable weight (dry weight).

Statistical Analyses

For Phase 1, analysis of variance (ANOVA) was used to determine if characteristics of soils differed at the different locations (A horizon outside gardens, and A horizon and B horizon inside gardens) and to determine if air temperatures were different at the different locations (upper and lower terrace, two sites in the valley). Tukey's studentized range test was used when the analysis of variance was significant to determine location differences. For Phase 2, ANOVA was used to determine differences between cobble and bare gardens for soil moisture, temperature, and biomass of garden plants. When the ANOVA showed significant differences, Tukey's studentized range test was used to determine garden differences. We performed all analyses using SAS statistical software (SAS Institute Inc., 1994). Unless otherwise indicated, a significance level of $P = 0.05$ was used.

RESULTS

Phase 1

All three excavated gardens in this study, which represent a range of garden conditions and locations within the local area, had sandy or loamy sand A horizons (Table 1). These sandy soils have relatively low water holding capacity (Table 1). The lower (B) horizons at all gardens had higher clay content and higher water holding capacity than the surface horizon (increase relative to the A horizon is significant at P<0.05, Table 1). The B horizons would hold water and reduce infiltration below this horizon, which would retain water within the top 20 to 40 cm soil depth. Both soil horizons inside the gardens had higher soilwater content at the time of collection than the A horizon outside of the garden. Soil organic matter was similar inside and outside of the gardens. Mineralizable N (the measure of soil fertility) was highest in the A horizon inside the gardens, lower (but not statistically significant) in the A horizon outside the gardens, and significantly lower in the B horizon within the plot (Table 1), which indicates that the B horizon has limited fertility.

Table 1. Summary comparison for soil characteristics of areas inside gardens, outside gardens, and for the B horizon inside gardens. Values are the mean of two samples from three sites at each indicated position.

	POSITION		
	A Horizon		B Horizon
Characteristic	Outside	Inside	Inside
% Sand	57 a*	65 a	55 a
% Silt	21 ab	24 a	18 b
% Clay	22 ab	11 b	27 a
% Organic Matter	2.25 a	2.09 a	2.22 a
Water Holding Capacity (ml water/g soil)	0.48 ab	0.38 b	0.54 a
Field Water Content (ml water/g soil)	0.02 b	0.082 a	0.085 a
Nitrogen Mineralization (ug N/g soil/day)	0.15 ab	0.28 a	0.04 b

*Within a row, values without the same letter are significantly different (P<0.05)

Although soil temperature data were limited, diurnal temperature fluctuations in the soil at the same depth were greater inside than outside the garden (Figure 4). Diurnal fluctuations in air temperature were greatest at the river valley sites and least at the garden sites on the terraces (Table 3). Also, mean air temperatures were colder at the valley sites than on the terraces ($P<0.05$), and absolute minimum temperatures during the measurement period were at or below freezing at the valley sites while the terrace was nearly a full 1° C warmer (Table 3).

Percent of bare soil and total plant cover inside the gardens showed little variability across sites, whereas all cover types showed wide variation in percent cover between sites outside the gardens (Table 2). In addition, plant species composition was more uniform inside than

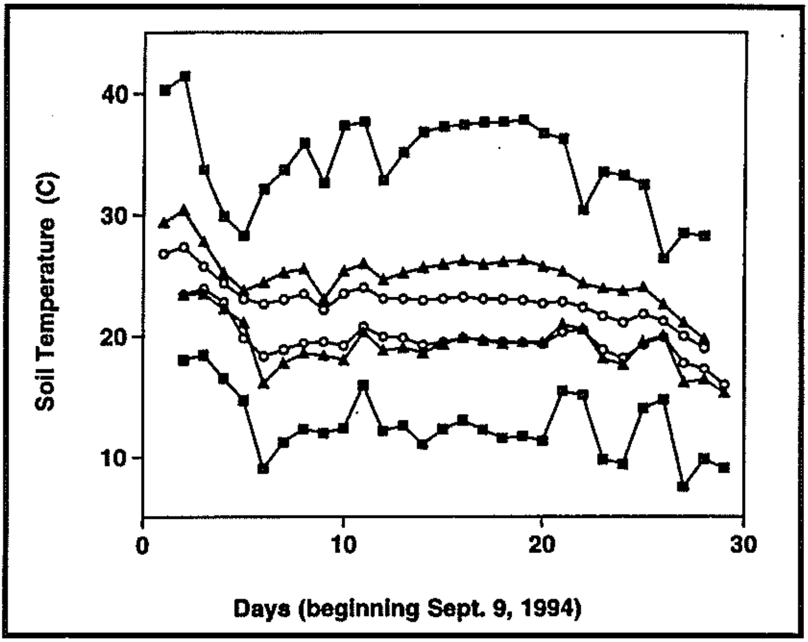

Figure 4. Daily maximum (upper lines) and mimimum (lower lines) temperatures of soil at 20 cm depth outside of the garden at Site 1 (circles), at 20 cm depth (triangles) and 2 cm depth (squares) inside the garden at Site 1 from Sept. 9 to Oct. 8, 1994.

Table 2 Percent ground cover of crytogamic crusts, litter, rocks, bare soil, and plants (total cover and listed by species) inside and outside the garden plots at each site.

		Percent Cover					
		Site 1		Site 2		Site 3	
Cover-type		Inside	Outside	Inside	Outside	Inside	Outside
Cryptogamic Crust		20.5	4.1	12.9	29	39.6	60.5
Litter		3.7	5.5	14.5	1.9	8.9	0
Rocks		49.2	5.6	42.9	10.2	19.3	18.2
Bare Soil		0	78.3	2.2	41	2.2	0
Total Plant Cover		26.7	10.5	29.4	22.3	30.9	25.8
Cover by Species Name	Common Name						
Bouteloua gracilis	Blue Grama	15.8	1.8	24.1		18.4	1.8
Bouteloua curtipendulum	Side-oats Grama	8.2	1				
Aristida longiseta	Red Three-awn	1.7					
Hilaria jamesii	Galleta	1	3.6	3.2	13.9	4.6	
Juniperous monosperma	One-seed Juniper			0.2			
Gutierrezia sarothrae	Snakeweed		4.1	1.9	4.4		3.6
Sporobolus airiodes	Alkali Sacaton				3.3	2.5	18.6
Sporobolus cryptandus	Sand Dropseed					2	
Sporobolus sp.	dropseed					1	
Opuntia polyacantha	Starvation Cactus				0.7	2.4	
Leucelene ericoides	White Aster						0.9

Table 3. Summary of maximum (Max.), minimum (Min.), and mean daily air temperatures at Anasazi sites near Ojo Caliente. Data were collected over the indicated days. On Sept. 24, 1994, the probe was severed at Garden Site #1. Temperatures are expressed as centigrade.

Site	Max.	Min.	Mean*	Std. Error	n
Sept. 10, 1994 to Sept. 24, 1994					
Garden Site #1	34.5	0.94	16.2 b	0.254	811
Garden Site #2	33.9	1.7	16.5 a	0.263	811
Valley near Barn	35.5	0.43	15.5 c	0.273	811
Valley east of River	31.6	1.96	15.7 c	0.263	811
Sept. 10, 1994, to Oct. 8, 1994					
Garden Site #2	34.4	1.2	15.96 a	0.198	1670
Valley near Barn	37.1	-0.81	14.88 c	0.205	1670
Valley east of River	33.5	0.18	15.02 b	0.198	1670

* For each time period, means followed by different letters are significantly different ($P<0.05$).

outside the gardens. The gardens were dominated by the native grama grasses with disturbance-related species increasing in cover and frequency outside the gardens. The greater concentration of rocks (including gravel and cobble) inside the gardens was evident at all sites. Erosion was evident at all sites, but it was most severe at Site 3 where nearly all the A horizon was missing and the B horizon was exposed outside of the garden. The exposed B horizon, which had higher clay content, supported a dense cryptogam cover (a complex community of microorganisms, also termed cryptobiotic). In contrast, Site 1 retained the sandy A horizon outside of the garden and cryptogam cover was nearly absent. The near absence of cryptogamic cover at Site 1 and high cover at Site 3 suggests better establishment and/or survival of cryptogamic crusts on soils with higher clay content.

Phase 2: Year 1

The cobble and bare plots were not significantly different for any soil characteristics at the beginning of the experiment (Table 4). Three days after completion of the cobble plots, soil moisture was not significantly different between plots (Figure 5). However, throughout the remainder of the experiment, soil moisture was significantly higher (range from $P < 0.05$ to $P < 0.001$) on the cobble mulch plots relative to the bare plots. Except for the day after completion of the cobble mulch plots, soil termperature was more stable in the cobbled plots than the bare plots, which had higher daily maximum and lower daily minimum temperature (Figure 6a, b, c, d, and e). This "buffering" of soil temperature occurred throughout the year, but was particularly noticeable in the summer months. During the hottest period, the bare plots had daily maximum temperatures in excess of 46° C (the maximum for the data loggers) and minimum temperatures below 20° C (Fig. 4c). In comparison, the cobble plots averaged maximum and minimum temperatures of 38 and 25° C, respectively. The cobble plots did not appear to warm earlier or cool later in the season than the bare plots.

Table 4. Initial soil characterizations of cobble and bare plots at the Plant Materials Center.

Characteristics	Units	Cobble	Std. Error	Bare	Std. Error
50% WHC	g water/g soil	0.158	0.003	0.16	0.004
Sand	%	89.5	0.045	89.5	1.323
Silt	%	1.25	0.629	1.25	0.946
Clay	%	9.25	1.109	9.25	0.854
Total N	ug/g	186.5	33.7	147.5	13.7
Total P	ug/g	136.5	14.9	108.5	5.3
N Min	ug/g	20.7	3.2	22.1	4.1

Note: No characteristics were significantly different (P>0.05)

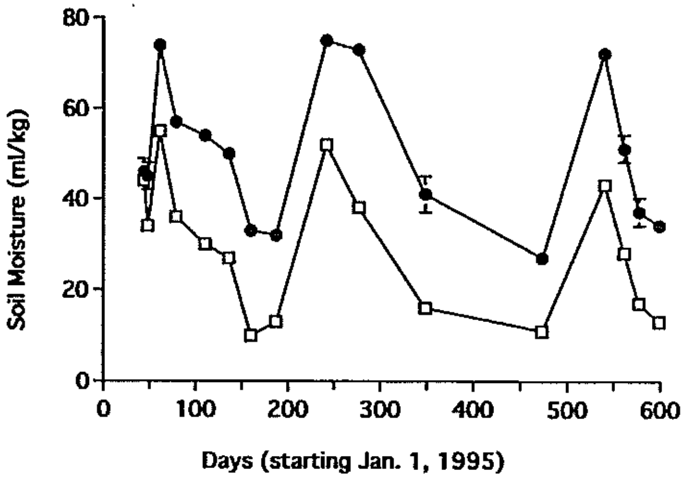

Figure 5. Changes in soil moisture within cobbled and bare experimental garden plots, beginning on Feb. 17, 1995, and ending on August 22, 1996. When visible, bars represent standard error of the mean (four replicate plots).

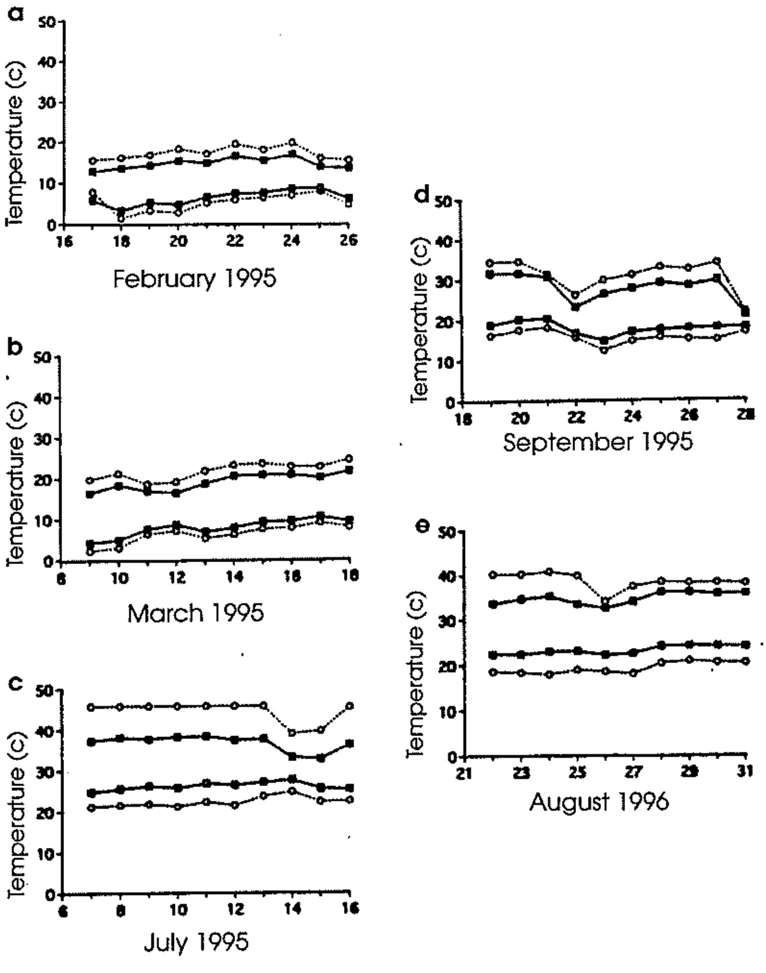

Figure 6. Average daily maximum and minimum temperatures on cobbled (filled squares) and bare (circles) experimental plots beginning after plot establishment (a), at onset of soil warming (b), during period of maximum temperatures (c), during fall cooling (d), and during the plant growth experiment (e).

Phase 2: Year 2

During the five days following transplanting, the Plant Materials Center received about 3.8 cm of rain (Fig. 5). Over the duration of the growth experiment, pan evaporation exceeded precipitation by about 40.6 cm, which indicates that potential evaporation exceeded water inputs. Supplemental water was given in equal amounts to all plants (alive and dead) over the remainder of the study, except during the period in late August when about 2.5 cm of precipitation occurred.

With only a few exceptions, all plants on the cobble plots survived and increased their biomass during the summer. After the first two weeks, the only plants to die on the cobble plots were two bean plants and a single squash plant. In contrast, many of the plants on the bare plots died or showed minimal growth after the first two weeks.

Without exception, every plant had equal or greater average weight on the cobble plots than on the bare plots (Table 5). Also, the total plant harvest from the cobble plots was nearly 4 times greater than from the bare plots (746 to 193 grams, respectively). The most dramatic difference between plots occurred in the Giant Sacaton, which grew to 1 m or more in the cobble plots and only 30 cm in the bare plots. The average dry weight of the Giant Sacaton was nearly 50 times greater in the cobble than in the bare plots (34.8 grams to 0.7 grams average weight, respectively). Other plants showed similar but smaller differences. Among the landscaping plants, the Blackfoot Daisy did especially well in the cobble plots, and in all plots in general. In contrast, Indian Ricegrass did not grow much after planting in the gardens, but still had more growth in the cobble plots.

In addition to every plant showing better growth on average, the plants had higher water content on the cobble plots than on the bare plots; 1.87 ml water per gram plant material on the cobble compared to 1.05 on the bare. The total amount of water in the plants on the cobble plots was nearly 4 times greater than in the plants on the bare

Table 5. Names of Plants, water requirements, and total harvest from cobble mulch experimental gardens.

			Average (mean) dry weight of 4 plots			
			Cobble		Bare	
Plant	Scientific Name†††	Water Req.††	grams*	S.E.†	grams	S.E.
Fernbush	*Chamaebatiaria millefolium*	Low/Med	2.84**	0.54	1.24	0.18
Rabbitbrush	*Ericameria nauseosa*	Low	4.2*	0.54	1.8	0.6
Purple Coneflower	*Echinacea purpurea*	High	3.9	0.9	2.4	0.94
Mormon Tea	*Ephedra viridis*	Low	1.19*	0.08	0.53	0.18
Apache Plume	*Fallugia paradoxa*	Low	3.64	1.03	1.11	0.66
New Mexican Olive	*Forestiera neomexicana*	Med.	5.98*	0.89	3.38	0.44
Blackfoot Daisy	*Melampodium leucanthum*	Low	16.5***	0.3	4.12	1.53
Purple Prairieclover	*Dalea purpurea*	Low/Med.	4.67	2.12	0.37	0.18
Indian Rice Grass	*Oryzopsis hymenoides*	Low	1.07***	0.12	0.035	0.018
Threeleaf Sumac	*Rhus trilobata*	Low/Med.	17.7***	0.89	10.6	0.72
Giant Sacaton	*Sporobolus wrightii*	Med.	34.6**	8.34	0.7	0.54
Hopi Red Corn (stalk)		Low	34.8*	8	13.2	0.94
Hopi Red Corn (cob)		Low	14.4*	4	1	0.27
Hopi Yellow Bean (plant)		Low	9.8*	2.37	1	0.45
Hopi Squash (plant)		Low	60	23.7	11.5	6.8
Hopi Squash (fruit)		Low	20.3	12.4	1.2	0.69
Total dry harvest			746**	145	193	20
Total water (ml)			2710**	439	696	148
Water content (ml) per gram plant			1.87**	0.015	1.05	0.078

†S.E. = standard error of mean

††Water requirements based upon "Albuquerque Plant List," Water Conservation Program, City of Albuquerque.

†††Scientific name based on Roalson and Allred (1995).

Means with asterisk(s) are significantly greater than bare plots (=$P<0.05$;**=$P<0.01$;***=$P<0.001$)

plots (2710 to 696 ml, respectively). Thus, regardless of how the results are compared, the results support the beneficial effect of cobbles on plant growth and plant water content.

DISCUSSION

The field investigation found that all the Anasazi gardens had sandy A horizons (sandy or sandy loam texture) and clay-rich subsoils. Sandy soils generally have high rates of infiltration, which would trap rain from intense summer thunderstorms, and have a greater amount of soil water able to be extracted by plant roots than do more clay-rich soils (Brady, 1984). Although this was not tested, it is believed that the Anasazi gardens were constructed by concentrating gravel and cobbles on the existing soil surface into smaller areas, and/or by mining suitable rocks from "borrow pits" located nearby. Initially the rocks would have been lying on the surface of the sandy A horizon. Similar soil conditions were created in the experimental gardens by spreading and compacting a clay-rich soil beneath about 30 cm of sandy topsoil. The experimental gardens were constructed to mimic the Anasazi gardens when they were first constructed. However, the function of the Anasazi and experimental gardens are expected to change over time.

The original gardens had rocks lying on and/or partially embedded in the soil surface. Studies have shown that rock or cobble mulches are effective in reducing raindrop impact, reducing soil sealing, increasing infiltration, and stabilizing soils (Jung, 1960; Meyer et al., 1972; Shanan and Schick, 1980; Abrahams and Parsons, 1991), provided the rocks are on the surface of the soil and not embedded in the soil (Poesen, 1986; Poesen et al., 1990). The experimental gardens provide empirical data that show direct evaporative loss is lower on cobbled areas, resulting in higher soil moisture under similar climatic conditions. Harvest from the gardens provide strong evidence that greater plant production occurred on the cobbled than on the bare plots provided with the same amount of water.

The function of the gravel surface would change as the rocks become filled with wind-blown particles (Gossens, 1994). The garden surfaces now have gravel and cobble embedded in the surface. Rocks that become embedded into the soil decrease infiltration and promote runoff (Poesen, 1986; Poesen et al., 1990). The Anasazi gardens are currently filled with grass and soil between the rocks, effectively putting the rocks at the soil surface. Thus, infiltration should be reduced relative to the conditions at time of their construction. Even with reduced rates of infiltration, the actual soil moisture was greater in the garden soils and cover of native plant species was greater in the gardens relative to outside the gardens.

Effects of past cultivation on soil chemical and physical properties vary substantially dependent upon the site characteristics and climate. Kalisz (1986) studied the effects of old-fields (used from 1800-1930) located on steep Appalachian slopes on soil properties. He found only minor differences in the properties of cultivated versus uncultivated soils; however, the lack of differences were attributed to the location of old-fields on sites characterized by favorable water regimes, and by deep, porous soils with uniform physical properties throughout the rooting depth. Surface soils of these landscape positions were resistant to permanent erosional degradation, and are rapidly rejuvenated by processes associated with reforestation. Anasazi cobble-mulch gardens did not change soil fertility as expressed by mineralizable N from that of soils outside the gardens. In contrast, Sandor et al. (1990) reported that areas used by Native Americans for agriculture in the Mimbres region of southern New Mexico had experienced soil erosion to the point that argillic (clay-rich) subsurface horizons were exposed. Sandor et al. (1990) found lower soil total N and P in the sites used for agriculture compared to uncultivated soils. The cobbles may have helped to retain soil fertility of the cobble gardens by protecting the surface soils from erosion. Thus, the effects of Native American agricultural practices on soil fertility and nutrients probably vary dependent upon the type of practice and the amount of erosion following cultivation.

Factors other than the presence of cobble may have acted to stabilize the soils and maintain soil fertility. The Anasazi gardens have an almost uniform coverage of cryptogamic crusts. The crusts may be important because they bind the soil and appear to contribute significant amounts of N to the soil (Loftin and White, 1996). Replenishment of soil N would be essential for long-term sustainable use of these plots for agricultural production.

There is one apparent discrepancy in the results from the experimental and Anasazi gardens. Cordell (1984) claimed that gravel-mulched gardens in the Rio Chama valley in Northern New Mexico stabilized soil temperatures (moderated temperature fluctuations) and increased overall soil temperature, which effectively extended the growing season. Results from the Anasazi gardens near Ojo Caliente support the suggestion of warmer soils in the gardens, but temperature fluctuation appears greater in the gardens than in the surrounding soil. Nearly the reverse occurred in the cobble gardens at the Plant Materials Center where soil temperature fluctuations were moderated, but overall temperature was not higher. The apparent differences in results might be related to a single factor; soil color. The cobbles used in the experimental gardens were light-colored granite cobble, which would reflect more sunlight than the tan-colored sandy soil. Rocks in the Ojo Caliente gardens also are derived from light-colored granites; however, the Anasazi gardens currently are darker than the surrounding sandy soils because of the dark-gray grass thatch and the dark cryptogamic crusts in the gardens. Thus, soil temperature of the Anasazi gardens when they were in use may have been different than present soil temperatures. The landscape position of the gardens on the terraces, which are above the cold air drainage in the valley, may be an important factor in extending the growing season in the Chama and Ojo Caliente valleys.

Lightfoot (1994) also suggested that pebble-mulch was used to increase soil temperatures, which promoted germination and growth of crops and extended the growing season. In contrast to the light-colored granites of the Ojo Caliente valley, the gardens in the Galisteo area studied by Lightfoot (1994) used rocks derived from the reddish granites of the Sangre de Cristo range, which are dark in color and would absorb more sunlight. The darker reddish rocks may function in the manner described, but again, the gardens are located on terraces above the river valley, which may play an equally important role.

Cobble gardens could have influenced areas much larger than the immediate gardens. Periman (1996) investigated the possible role of cobble gardens on the general landscape. The hypothesized primary function of the cobble is to reduce direct evaporative loss of soil moisture, but cobbles also protect the soil surface from erosive forces of rainsplash, which could reduce erosion and, together with promoting infiltration, reduce total runoff. In research focused on increasing recharge to groundwater, Kemper et al. (1994) determined that gravel mulches 5 cm thick resulted in accumulation of 80 to 85% of the annual precipitation in the soil beneath the mulch. This research, which was conducted near Ft. Collins, CO, attributed less accumulation of moisture beneath thinner mulches and unmulched soils to greater evaporative loss. Thus, the cobble gardens could have increased groundwater recharge and might have increased base-flow or extended the period of flow in local rivers.

Cobble-mulch may prove to be an effective technique in arid land restoration. The primary goals of arid land restoration are to control soil erosion and increase water availability to plants. Effective restoration techniques stabilize soils and increase infiltration of precipitation. This results in retention of the resources (water and soil nutrients) required for recovery of former structural and functional properties. As stated above, rock or cobble mulches are effective in reducing raindrop impact, reducing soil sealing, increasing infiltration, and stabilizing soils, provided the stones are on the surface of the soil and not embedded in the soil. Cobble-mulch/gravel treatments have been successful in stabilizing and reclaiming disturbed areas such as mined-land (Mayer et al., 1981) and roadbeds (Kochenderfer and Helvey, 1987).

Cobble mulch treatments may prove to be particularly effective in locations where the primary disturbance is grazing. Cobble mulch should "armor" the soil surface and protect it from compaction by livestock trampling and other physical disturbances. The mulch prevents livestock from grazing too close to the soil surface and thereby damaging plants, and the rocks tend to "anchor" the grasses that might otherwise be pulled from the soil. From a landscape perspective, selectively applied cobble mulch treatments within watersheds would intercept runoff from upslope areas and stabilize treated and downslope areas. Mulched areas could serve as refugia and points of dispersal for native vegetation within a degraded landscape. This type of treatment may provide for restoration of landscape structure (including heterogeneity) and function without having to treat the entire landscape.

The benefits of cobble as mulch have been recognized by some landscaping professionals. The use of mulch is a fundamental consideration in developing a water-efficient landscape, or "Xeriscape" (Crocker, 1989; Johnson and Millard, 1993; Knopf, 1991; Springer, 1994; Phillips, 1995). The ubiquitous use of gravel-covered black plastic as a substitute for grass sod in the arid regions of the U.S. has met with disdain by most landscape architects, designers, and horticulturists as an ecologically and aesthetically dismal landscape practice. The landscape resulting from this practice has been coined as "zeroscape" in contrast to the water-conserving landscape practices of "Xeriscape" (Knopf, 1991). The traditional procedure of laying plastic beneath gravel negates the positive effects of the gravel on soil moisture, aeration, and soil friability identified in this study.

Gravel mulches have been effectively used for porous paving and informal pathways as well as for lining dry streambeds and drainage basins (Phillips, 1995). Larger gravel and cobble have been used to stabilize the surface of slopes to allow vegetation to become established (Phillips, 1995). Stone or gravel mulches are used around plant species requiring a well-drained surface (Crocker, 1989; Phillips, 1995).

Some landscape professionals propose that gravel mulch provides a well-aerated surface and the mulch recycles moisture by condensing moisture due to the alternating daytime heating and nighttime cooling of the gravel (Phillips, 1995). Because of weed emergence through rock mulches, which occurred in this study, many landscapers recommend the use of porous weed barrier fabric (either woven or spun-bonded) beneath the mulch (Springer, 1994; Phillips, 1995).

CONCLUSIONS

The technology of cobble mulch gardening, landscaping, and land restoration will involve complex interactions between the mulch, the underlying soil profile, and changes that will occur as the features age. This research has shown that primary factors will include the thickness and texture of the soil in the rooting zone as well as the depth of clay, caliche, or other water-impeding layers. Soil moisture is definitely increased under cobble mulch by reducing water-loss through evaporation. Gardens constructed with light-colored rocks may moderate soil temperatures, which makes for a favorable rooting environment. But gardens constructed with darker-colored rocks may increase soil temperatures, which may be beneficial in cooler environments by extending the growing season. All types of plants grew as well or better on the cobble gardens than on the gardens without cobbles in this experiment, but results may differ in soils of different texture. In sandy soils, this research indicates that total water consumption by gardens and landscaping would be greatly reduced if about 7 cm depth of cobble mulch was applied to the soil surface.

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WASTEWATER TREATMENT IN NEW MEXICO

Amy Russell[85] and Ricardo B. Jacquez[86]

INTRODUCTION

Wastewater treatment, as we know it, was started in 1972 when the Clean Water Act (CWA) was passed. Regulated by the Environmental Protection Agency (EPA), the CWA sets standards for water quality and water treatment techniques (Sullivan, 1995). The EPA assigned primacy for monitoring wastewater treatment facilities to the states. In New Mexico, the New Mexico Environment Department (NMED) sets standards for and monitors the wastewater treatment facilities, and then reports back to the EPA. The standards, which the state sets must be at least as stringent as the EPA's standards which were set in the CWA (Sullivan, 1995).

There are two types of water systems into which wastewater treatment facilities release their treated effluent, groundwater and surface water. The NMED requires facilities to have permits to discharge their treated water into either of the two water systems. To release into surface water, a National Pollutant Discharge Elimination System (NPDES) permit must be issued by NMED (as directed by EPA). An NPDES permit states the location of the facility, the water quality standards that the facility must meet, and the monitoring and reporting

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[85] Environmental Engineering Graduate Student, New Mexico State University, Las Cruces, NM 88003, amrussel@nmsu.edu

[86] Director, Educational Programs, Waste-management Education & Research Consortium (WERC), New Mexico State University, Las Cruces, NM 88003, rjaquez@nmsu.edu

requirements (Sullivan, 1995). To release to groundwater, the facility must apply for a Groundwater Discharge Permit issued by NMED. This permit is similar to the NPDES permit, but it is not directed by EPA. New Mexico is concerned about its groundwater and therefore decided it needed regulations to protect its quality for future use.

SOURCES AND CHARACTERISTICS OF WASTEWATER

Wastewater comes from two sources: industry and municipalities. Municipal wastewater is collected from homes and businesses from around the community. It contains a wide variety of contaminants, such as soaps from washing, human wastes, food wastes, and paper wastes. Most of these contaminants remain suspended in the wastewater, and are therefore termed suspended solids. Contaminants that dissolve in the wastewater are usually organic in nature (proteins, sugars and starches) and are termed soluble organics. Also, human wastes contain pathogens and coliform bacteria. Coliform bacteria are not directly related to pathogens, but if the water is contaminated with coliform bacteria it is possible that the water contains pathogens. So that disease does not spread, these pathogens must be killed. Therefore, wastewater must be treated to remove the solids, pathogens, and organics before it is released into water systems.

EPA has requirements for all of these contaminant types in the conventional wastewater treatment facility. Biochemical Oxygen Demand (BOD) is the term EPA uses to describe organics. To remove the organics, oxygen is used by bacteria to transform the biodegradable material to carbon dioxide and water. EPA requires that treated wastewater contain less organics than it takes to use up 25 mg/L of oxygen in the receiving stream. Another acronym EPA uses is TSS (Total Suspended Solids). EPA requires that the TSS be reduced to a concentration of 30 mg/L. A technology readily available to directly measure pathogens does not exist. Coliform bacteria are monitored by facilities as a signal for pathogens. Therefore, EPA requires a treatment process, disinfection, designed to kill pathogens and coliform bacteria (Peavy, Rowe, and Tchobanoglous, 1985).

FINANCING WASTEWATER TREATMENT PLANTS

Financing for wastewater treatment plants is obtained through the EPA's Construction Grant Program. EPA provides federal funds (83%) and matching state funds (17%) to be borrowed by the community through the State Revolving Fund (SRF). Communities are given the opportunity to borrow money for construction or repairs. The communities then use part of the city's taxes allocated to the wastewater treatment facility to pay back the loan. Repayment of the loan replenishes the supply of money to be borrowed. The SRF will be able to fund wastewater facilities far into the future (EPA - Office of Water, 1998).

Operation and maintenance (O&M) of wastewater treatment facilities include labor, energy (gas or electric), chemicals (chlorine), materials, and supplies. Funding for O&M of the wastewater facility is supplied by the communities' taxes. Small communities have less money coming into their fund, so low O&M facilities are better for their budgets. Large cities have more tax money and more water entering the wastewater treatment facility. Therefore, O&M costs can and will be greater than small communities (EPA - Office of Water, 1998).

WASTEWATER TREATMENT BASICS

There are many technologies used to treat wastewater. These technologies are used in one or more of the following treatment systems; pretreatment, primary treatment, secondary treatment, tertiary treatment, and sludge management (Peavy, Rowe, and Tchobanoglous, 1985). Figure 1 shows a common flow diagram for a conventional wastewater treatment facility. The most popular treatment technologies are discussed below.

Pretreatment

Pretreatment is used to remove large solids, such as tree branches, rocks, and rags, from the wastewater. This stage protects the equipment used

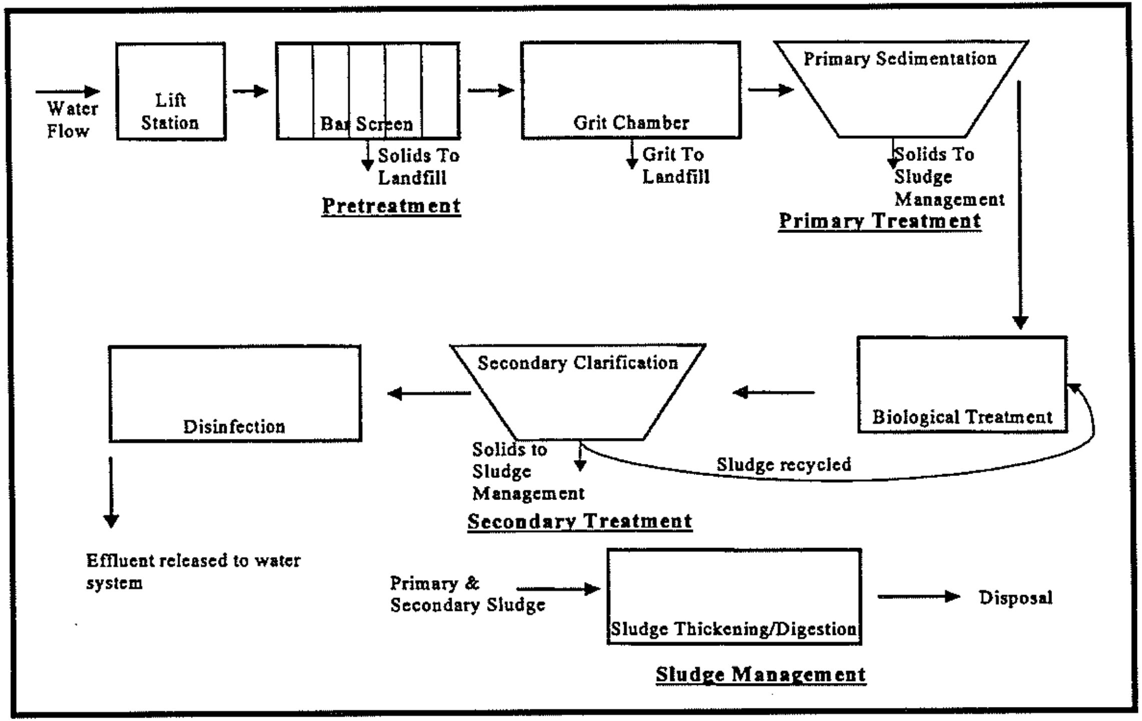

Figure 1. Flow Diagram for a Conventional Wastewater Treatment Facility

for further treatment (Peavy, Rowe, and Tchobanoglous, 1985). The debris collected from these processes is not harmful and is usually trucked to the landfill without additional treatment. The debris removal does not contribute to meeting EPA requirements. One or more of the following devices may be used in a wastewater treatment facility.

Lift Station: Most wastewater treatment facilities prefer to have the water flow through the treatment processes by gravity. To accomplish this the wastewater coming into the facility may be lifted to a higher elevation to allow gravity to create the flow.

Screening: Large screens are placed at the entrance to the facility to remove large debris. The screens in a small facility may be cleaned manually by scraping. Large facilities, however, may implement mechanical cleaning techniques.

Comminuting: The comminutor is a shredding machine, which chops the large debris into pieces that can easily pass through the remaining wastewater treatment equipment.

Grit Removal: Grit is the sand, silt, pebbles, seeds, coffee and tea grounds, and metal fragments that enter with the wastewater. It is important to remove the grit because of the wear and tear on the equipment. To remove grit, a settling area is created in the facility's piping system. It is usually an enlarged area, which allows the water flow to slow, letting the grit settle to the bottom (Peavy, Rowe, and Tchobanoglous, 1985).

Primary Treatment

Primary treatment is for the initial removal of suspended solids. Up to 40% of the BOD is removed and up to 70% of the TSS is removed (Peavy, Rowe, and Tchobanoglous, 1985; Tchobanoglous and Burton, 1991).

Primary Sedimentation: This is the first stage where water quality is affected. Once the large debris and grit is removed, the wastewater flows into a large settling basin. Some suspended particles stick to each other becoming heavier than the water and settle to the bottom of the basin. Other particles, such as oil and grease, float to the surface of the water in the basin. The sludge is collected from the bottom and skimmed from the top and sent to the sludge management area (Peavy, Rowe, and Tchobanoglous, 1985).

Secondary Treatment

Secondary treatment is for the removal of the remaining solids and organics. This stage is the biological phase. A mixed culture of microorganisms metabolizes or degrades the solids and organics, converting the food into new microorganisms. The new microorganisms are separated from the wastewater by physical settling as sludge which is recycled or sent to the sludge management area (Peavy, Rowe, and Tchobanoglous, 1985). One or more of the following devices can be used for this purpose.

Activated Sludge: Sludge that contains the living microorganisms is known as Activated Sludge. The sludge is pumped back into the activated sludge basin, where the microorganisms continue to multiply and degrade more of the unwanted solids and organic materials. Air must be supplied to the basin so that the microorganisms have the needed oxygen to survive (Peavy, Rowe, and Tchobanoglous, 1985). There are numerous modifications to the basic activated sludge process (Tchobanoglous and Burton, 1991). The activated sludge system removes an average of 90% of the remaining BOD.

Ponds and Lagoons: Wastewater ponds and lagoons are synthetic or clay-lined basins that have a detention time from 60 to 120 days so that the naturally occurring microorganisms are able to digest the unwanted solids and organics. In a lagoon, oxygen is supplied by the air through natural diffusion. In a pond, oxygen is supplied by mixing (Peavy, Rowe, and Tchobanoglous, 1985).

Fixed Film: In a fixed film process, the microorganisms are attached to a filter made of rock, plastic or wood. The microorganisms degrade the solids and organics as the water flows over the filter media. The microorganisms that die become unattached to the media and drop to the bottom of the basin, are collected, and sent to the sludge management area (Peavy, Rowe, and Tchobanoglous, 1985). The most common fixed film process is the trickling filter. The trickling filter's media is suspended in a large basin where the water flows over the media and microorganisms. Another modification to the fixed film process is the Rotating Biological Contactor. Like the trickling filter, the microorganisms are attached to a media. Unlike the trickling filter, the media is rotated through the wastewater, allowing the microorganisms to metabolize the unwanted organics (Tchobanoglous and Burton, 1991).

Secondary Clarification: Once the organics have been consumed by the microorganisms and metabolized into cell mass, the wastewater may contain live or dead organisms, which need to be removed. The wastewater is collected in a settling basin so that remaining microorganisms can be settled and recycled or sent to the sludge management area (Peavy, Rowe, and Tchobanoglous, 1985).

Disinfection: The most common disinfectant is chlorine. Chlorine is added to reduce the number of pathogens that may be present in the wastewater, especially if the wastewater is discharged to a lake or stream which has the potential for human contact (Peavy, Rowe, and Tchobanoglous, 1985).

Tertiary Treatment

Tertiary treatment is designed to remove the remaining solids and nutrients (such as nitrogen and phosphorous). Nutrients must be removed so that the receiving stream does not have a sudden growth of algae or bacteria, which is referred to as a "microbial bloom." The microbial bloom would remove oxygen from the water, which, in turn, would take oxygen from other desirable aquatic biota (Peavy, Rowe, and Tchobanoglous, 1985). This type of treatment is required if a facility releases its treated wastewater into a lake or a trout stream. This treatment is not normally required if the facility releases its treated wastewater to groundwater or a non-trout stream.

Filtration: There may be a small portion of solids that the secondary clarifier was not able to collect. So, to remove those solids, the wastewater is typically passed though a sand filter. The maintenance of the filter is time consuming and costly, so unless the wastewater is to be released to delicate waters, no filtration is used (Peavy, Rowe, and Tchobanoglous, 1985).

Nitrogen Removal: The nitrogen in the wastewater is usually present as ammonia (NH_3). To remove it, a facility can use one of two methods, air-stripping or nitrification-denitrification. In air-stripping, the pH of the wastewater is raised to 11 by the addition of lime, and then air is pumped through the wastewater, which releases the ammonia into the air. Air-stripping is expensive, so unless the pH of the water needs to be raised for another process, air-stripping is not used.

The nitrification-denitrification system is the most commonly used process to remove nitrogen. It is a two step process in which specific microorganisms are used to convert NH_3 to Nitrate (NO_3^-) and then to nitrogen gas (N_2) (Peavy, Rowe, and Tchobanoglous, 1985).

Phosphorous Removal: The most common phosphorous removal is a chemical process, where iron or aluminum is added to form a precipitate with the phosphorous (Peavy, Rowe, and Tchobanoglous, 1985). The iron or aluminum can be added at different stages in the wastewater treatment process. The best phosphorus removal is when the chemicals are added after primary treatment, so the collection of the precipitate is accomplished in the secondary clarifier (Tchobanoglous and Burton, 1991).

Sludge Management

Sludge management is the conditioning and disposal of sludge. Concentrated organics, solids, and pathogens are contained in the sludge. Disposal of this sludge must be completed in an environmental friendly and economical way. The facility's disposal plans determine the type of treatment the sludge undergoes (Peavy, Rowe, and Tchobanoglous, 1985).

Sludge Thickening: Since the sludge is mostly water, the water must be removed. The most common type of sludge thickening is by gravity. The sludge is collected in a settling basin and given time to settle to the bottom, where it is collected for disposal (Peavy, Rowe, and Tchobanoglous, 1985). If the sludge is to be incinerated, more water needs to be removed, so the sludge may be concentrated using a centrifuge.

Sludge Digestion: The most common sludge digestion process is anaerobic digestion. Without oxygen, the microorganisms that survive do not reproduce as fast as the microorganisms that live in oxygen rich environments. Therefore, these anaerobic microorganisms not only reduce the amount of sludge, they do not increase the amount of living organisms. The sludge is converted to methane (CH_4), which can be burned to produce energy for heating and electricity (Peavy, Rowe, and Tchobanoglous, 1985).

Aerobic digestion is commonly used in small communities. It uses microorganisms to degrade the sludge into a humic-like end product. Oxygen is supplied by mixing. It does not reduce the amount of sludge as efficiently as anaerobic digestion, but it is easier to operate and also costs less initially (Tchobanoglous and Burton, 1991).

Sludge Drying Beds: Another method to remove water is through drying beds. The watery sludge is spread onto a sand bed where the water is drained to a collection system under the bed. Some of the water evaporates, but most water drains to the collection system. Sludge drying beds are inexpensive and require little maintenance (Tchobanoglous and Burton, 1991).

Sludge Disposal: The type of disposal a facility chooses determines the type of treatment for the sludge. There are basically three types of sludge disposal: incineration, placement in a landfill, and land application. Incineration is the burning of the sludge. Once burned, the ashes are sent to a landfill. Placement of the sludge, after removing excess water, in a landfill, without incineration is accomplished by injection of the sludge 12 to 18 inches below the surface. Land application is the most complex of the three disposal types. The treatment of the sludge depends on the type of land the sludge is to be applied. The regulations for land application are less stringent as the facility moves the application away from human contact. All land application sludge is required to be treated to reduce pathogens.

Alternatives to the Wastewater Treatment Facility

The most common alternative to the wastewater treatment plant is a constructed wetlands. A constructed wetlands is a passive treatment that allows the wastewater to flow through a constructed bed of rocks covered with microorganisms that will break down the solids and organics, and plants to remove any unwanted nitrogen, phosphorous, and heavy metals (Gillette, 1992). Before the wastewater is released into the constructed wetlands, it must pass through the pretreatment stage to remove large solids. This type of treatment is low maintenance, but it requires a large amount of space and a long detention time. Because of the space and time issues, this type of facility is not practical for cities of populations over 5,000.

NEW MEXICO'S WASTEWATER TREATMENT FACILITIES

Table 1 shows selected cities from around New Mexico and the type of wastewater treatment employed. Almost half (48%) of New Mexico's wastewater treatment facilities require an NPDES permit and a Groundwater Discharge Permit. Duel permitting is required because the treated wastewater may be released to a river, which requires an NPDES permit, and the sludge is applied to the land, which requires a Groundwater Discharge Permit. Artesia, NM has another common situation. Artesia's facility releases the treated wastewater to the river part of the year, and uses the effluent to irrigate the golf course the other part of the year (Coffman, 1998).

A majority (67%) of the facilities uses activated sludge for their secondary wastewater treatment. Las Cruces has a unique situation. The facility uses activated sludge and trickling filters for their secondary treatment.

Most (85%) of the facilities are not required to have tertiary treatment, and a small percentage (10%) have constructed wetlands.

Anaerobic digestion is used at most facilities (43%) for sludge treatment. About one-third of the facilities use aerobic digestion, two-thirds of the facilities use sludge drying beds, and 72% of the facilities dispose of the treated sludge by land application.

The Rio Grande collects the most (41%) treated wastewater, with the Pecos River collecting 24%.

CONCLUSION

Wastewater treatment has become an important issue for most communities. As the population continues to grow, it is important to look at the most appropriate technology for the community. If a facility is

Table 1. Selected Cities Around New Mexico and their Wastewater

City	Type of Permit	Secondary Treatment	Tertiary Treatment
Albuquerque,	NPDES* & GWDP**	Activated Sludge	Required
Artesia, NM	NPDES & GWDP	Fixed Film	Not Required
Carlsbad, NM	NPDES	Activated Sludge	Not Required
Cloudcroft, NM	NPDES	Fixed Film	Not Required
Clovis, NM	GWDP	Activated Sludge	Not Required
Farmington, NM	NPDES & GWDP	Fixed Film	Not Required
Gallup, NM	NPDES & GWDP	Activated Sludge	Required
Hobbs, NM	GWDP	Activated Sludge	Not Required
Las Cruces, NM	NPDES & GWDP	Activated Sludge/ Fixed Film	Not Required
Las Vegas, NM	NPDES & GWDP	Activated Sludge	Not Required
Los Alamos, NM	NPDES	Fixed Film	Not Required
Moriarty, NM	GWDP	Activated Sludge	Not Required
Raton, NM	NPDES	Activated Sludge	Not Required
Roswell, NM	NPDES & GWDP	Fixed Film	Not Required
Santa Fe, NM	NPDES & GWDP	Activated Sludge	Required
Silver City, NM	NPDES & GWDP	Activated Sludge	Not Required
Socorro, NM	NPDES	Activated Sludge	Not Required
Taos, NM	NPDES	Activated Sludge	Not Required
Tatum, NM	GWDP	Constructed Wetlands	
T or C, NM	NPDES & GWDP	Activated Sludge	Not Required
Tucumcari, NM	NPDES	Constructed Wetlands	

* NPDES - National Pollutant Discharge Elimination System Permit
**GWDP - Groundwater Discharge Permit

Treatment Methods (Coffman, 1998, and Kniskern, 1998)

	Sludge Treatment / Disposal	**Receiving Stream**
	Anaerobic Digestion / Composting or Land Injection	Rio Grande
	Anaerobic Digestion / Land App.	Pecos River
	Anaerobic Digestion / Composting	Pecos River
	Anaerobic Digestion / Drying Beds / Land App.	Fresnal Canyon
	Anaerobic Digestion / Composting / Land App.	N/A
	Anaerobic Digestion / Drying Beds / Land App.	San Juan River
	Aerobic Digestion / Drying Beds	Rio Puerco River
	Lime Stabilization / Land App.	N/A
	Anaerobic Digestion / Drying Beds / Land Injection	Rio Grande
	Aerobic Digestion / Drying Beds / Land App.	Pecos River
	Aerobic Digestion / Drying Beds	Rio Grande
	Aerobic Digestion / Drying Beds / Land App.	N/A
	Drying Beds / Land App.	Canadian River
	Anaerobic Digestion / Drying Beds / Land App.	Pecos River
	Anaerobic Digestion / Drying Beds / Land App.	Rio Grande
	Aerobic Digestion / Drying Beds / Land Reclamation	San Vicente Arroyo
	Aerobic Digestion / Land Injection	Rio Grande
	Aerobic Digestion / Drying Beds / Land App.	Rio Grande
	Not available	N/A
	Drying Beds / Land App.	Rio Grande
	Anaerobic Digestion / Drying Beds / Land App.	Breens Pond

designed to treat wastewater for a small town, a passive treatment, such as constructed wetlands, may be the best technology. If a facility is intended to treat sewage for a larger city, the facility may not have the space or time for a passive treatment, so the conventional wastewater treatment facility would be best. Of course, there are combinations of the above treatment techniques, which makes planning a wastewater treatment facility an interesting and complicated task.

Persons interested in career opportunities designing wastewater treatment plants and other environmental facilities should contact the Waste-management Education & Research Consortium (WERC) at 1-800-523-5996.

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POTENTIAL FOR GREYWATER RECYCLE AND REUSE IN NEW MEXICO

S. Trujillo[86], A. Hanson[87], W. Zachritz II[88], and R. Chacey[89]

ABSTRACT

One relatively new on-site, natural, alternative wastewater disposal technique involves segregating the wastes produced in a household into two types of waste to be treated separately: blackwater and greywater. Blackwater is defined as the wastewater from the toilet and garbage disposal, and greywater includes all the remaining wastewater in a home. Separating the waste allows for more efficient treatment. Treated greywater can supply landscape irrigation for a home. Unfortunately, in most cities around the U.S. greywater recycling is illegal because of outdated state regulations. Due to the decrease in water quality and quantity, many states have been forced to evaluate water conservation alternatives such as greywater recycling. Most current state regulations do not include the alternative of greywater reuse. However, as of March 1, 1995, thirteen states have incorporated greywater reuse into their regulations (NSFC, 1995). This increase shows that progress is being made toward acknowledging greywater as a resource. The State of New Mexico is currently developing regulations for the use of greywater, and interim guidelines are currently available.

INTRODUCTION

In conventional wastewater treatment processes, greywater, a potential source of usable water, is mixed with blackwater and becomes a

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[86] Master's Student at Notre Dame University

[87] Associate Professor, Civil, Agricultural, and Geological Engineering , New Mexico State University

[88] Director of Environmental Systems Research, Southwest Technology Development Institute, New Mexico State University

[89] Drinking Water and Community Services Bureau, New Mexico Environment Department

more complicated treatment problem. Residential greywater recycling provides reuse of this water in an acceptable, safe manner. When greywater is separated from blackwater, it requires only minimum treatment before it can be used for non-contact household applications, such as landscape irrigation, subsurface indoor plant water, and toilet flush water in a household (Foster et al. 1994). Many types of greywater recycling systems are in use. They range from a hose directly connected from a drain fixture to the garden, which has been referred to as "throwing it out the window the way my granny used to" (Nesbitt, 1977), to a number of integrated treatment systems such as settling tanks, sand filtration units or constructed wetlands. An ideal residential greywater recycling system would collect water from all of the fixtures in the house except the toilet and the garbage disposal, treat the water on site, and then use the water for watering plants using subsurface irrigation inside and outside of the home. Studies performed on the Casa del Agua proved greywater recycling and the use of water-efficient fixtures dramatically reduce daily water consumption from 148 gallons per capita per day to 35 gallons per capita per day (Karpiscak et al., 1990). According to Karpiscak et al., the largest source of water savings at Casa del Agua is due to the greywater recycling units, which allows double use of the water.

On November 9, 1994, California became the first state to legalize the separation and use of greywater for landscape irrigation statewide (Wilson, 1995). Many states, including New Mexico, are following suit. A few states which have already incorporated greywater reuse into their regulations, did so because many homes in the state were illegally reusing greywater. The conclusion made by the regulators was that if a large number of people continue to defy the law at least some information should be available to them to set up a safe and viable system. Regulations need to encompass design parameters which will meet safe effluent standards. Greywater in New Mexico is defined in 20 NMAC 7.3, Part 1, 104.R.

GREYWATER CHARACTERISTICS: QUANTITY AND QUALITY

Greywater Quantity

Greywater provides a large resource which can be reused. Greywater is water that has not been directly contaminated by fecal material, and has commonly been depicted as water that is dirty, but not unsanitary (Warshall, 1979). Greywater composes approximately 60-70 percent of the total wastewater produced in a home (Nesbitt, 1977). Table 1 lists the types of water included in New Mexico's regulatory definition of greywater and where it can be applied.

Table 1. Partitioning of Wastewater in New Mexico

Water allowable above ground	Water allowable below ground	Non-re-usable Water
condensation pans	bathroom sinks	toilets
refrigerators	bathtubs	bidets
air conditioner	showers	urinals
reverse osmosis reject	laundry facilities	water softener backflush
hot tub (Jacuzzi) drains	dishwashers	saltwater aquarium drains
freshwater ponds, pools	kitchen sink (w/o garbage disposal)	swimming pool drains
fountain drains		
aquarium drains		
outdoor showers (sand removal)		

Any sink or drain which may have chemicals poured down it is restricted and cannot be used as a source of greywater; examples would be: laundry room sinks when used for wastes other than laundry; utility sinks in garages and on patios when used to dispose of hazardous waste; garden and greenhouse sinks or floor drains if cleaned with chemical cleaner.

Residential greywater content is highly variable depending on the residence (Karpiscak et al., 1990). Design engineers for Casa del Agua ran an experiment using two families living at separate times in the home. The greywater production was monitored from each family and each family showed distinctly different water usage patterns which corresponded to the quality of the greywater (Karpiscak et al., 1990). To quantify this, variables such as volume of flow and whether diapers or other such laundry are going to be washed need to be identified before the design is implemented. Greywater quantities, by fixture are presented in the Table 2 (NMED, 1997).

Table 2. Greywater Production by Fixture or Appliance

Fixture/Appliance	Range	Typical	Units
automatic washing machine	35-60	50	gal/load
automatic dishwasher	4-10	6	gal/load
bathtub	20-30	24	gal/use
shower	10-25	18	gal/use
washbasin	.75-2	1.25	gal/use
shower head	2.5-7	3.5	gpm
sink faucet	0.5-3.5	2.0	gpm

These rates are used in estimating the greywater production for a specific household. A number of additional assumptions are needed. In the state of New Mexico, one assumes that all of the bedrooms in a house have two occupants and that each occupant washes their hands

3-5 times/day, showers once/day, and makes reasonable assumptions regarding laundry and dishwashing. A safety factor of 1.5 is used to insure the grey water treatment system will be large enough. Specifics on these calculations are available from the New Mexico Environment Department (NMED). Some states simplify the calculations by allowing the homeowner to estimate flow quantity based on the number of bedrooms in the home. The per bedroom flow specified in these regulations is based on 150 gal/bedroom per day for the first two bedrooms and 75 gal/bedroom per day for each additional bedroom. For example, a three bedroom home would be 375 gpd. Stormwater drains cannot be connected to greywater systems because the quantity of water generated during a storm event is too large for a greywater system to handle. The stormwater can be harvested for irrigation, but the systems should be completely separate.

Greywater Quality

Greywater is contaminated by whatever goes into the household drain; the constituents may be: soaps, detergents, perspiration, organics, grease, hair, dead skin, bacteria, viruses, and more. From a treatment perspective, greywater is characterized by high biochemical oxygen demand (BOD), high levels of suspended solids, high levels of nutrients, high salt content, and a wide variety of microbials (Karpiscak et al., 1990). Table 3 shows the pollutant concentrations for four of these pollutants in major residential wastewater sources.

Table 3. Pollutant Concentrations in Major Residential Wastewater Sources (mg/L)

Pollutant	**Toilet**	**Greywater**	**Garbage Disposal**	**Combined Wastewater**
BOD_5	280	260	2380	360
Suspended Solids	450	160	3500	400
Nitrogen	140	17	79	63
Phosphorus	20	26	13	23

Adapted from: EPA(1980) Design Manual: Onsite Wastewater Treatment and Disposal Systems.

The above pollutant concentrations are higher for toilet water and garbage disposal wastes than in greywater, except for phosphorus, a plant nutrient. For treatment purposes, garbage disposal wastes are grouped together with blackwater because of the high organic content. The waste characteristics are important in designing a treatment system.

BOD is related to the amount of oxygen required by organisms to biodegrade organic pollutants. The higher the organic pollution, the higher the BOD. Metcalf and Eddy suggest that 220 mg/L is a medium concentration while a value of 400 mg/L would be considered a strong concentration (Metcalf and Eddy, 1979). The concentration in a typical sample of greywater (260 mg/L) is close to that of typical blackwater (280 mg/L). This suggests that greywater has almost the same amount of organic matter as blackwater. Organic matter is easily decomposed in soil and therefore is not a major concern if the water is to be used in irrigation.

Suspended solids are defined as the amount of solids suspended in the wastewater as opposed to those dissolved in the water. It is expressed in units of mg/L. For comparison, a concentration of 100 mg/L would be considered weak , while 220 would be considered a medium concentration (Metcalf and Eddy, 1979). Greywater has a significantly smaller amount of suspended solids than blackwater. Suspended solids can be removed in a settling basin or by filtration. However, the lower the suspended solids level, the less treatment that must be performed.

Nutrient levels are often higher in greywater than blackwater. The most common nutrients are nitrogen, and phosphorus. According to Metcalf and Eddy, a strong concentration would be approximately 85 mg/L for nitrogen and 15 mg/L for phosphorus (Metcalf and Eddy, 1979). Nitrogen concentrations in greywater are relatively low and should not be a contaminant of high concern, if the water is used to irrigate actively growing plants. Approximately 60-70% of the nitrogen is contained in the blackwater. Phosphorus is present mainly due to the detergents in the greywater (Wilson, 1995). Nutrients, in small concentrations, are beneficial resources for plants. An overdose of any nutrient can upset the balance of a natural system and ruin natural communities through eutrophication.

Salt is another pollutant of concern. Greywater has high levels of sodium and chloride (Gelt, 1993). If greywater is used over time for irrigation directly on soil, the salts present will build up to levels harmful to plants. Salts are usually introduced into greywater through laundry detergents. The characteristics of an ideal detergent are given by Chacey in NMED (1997) as:

> liquid, not a powder (less sodium and filler material)
> zero sodium or additives which contain sodium compounds
> zero boron
> zero water softeners (vs. clothes softeners)
> zero chlorine
> zero alkylbenzene or other petroleum distillates

A list of greywater recycle friendly products is available from the New Mexico Environment Department. Note: Because of salt content, **No regeneration water** from a water softener can be used as irrigation water.

The pollutants of greatest concern in greywater are the microbial pathogens. Microbials come from the washing machine and from bathing. Health risk information is limited, and this is the reason greywater reuse has been banned in many states (Karpiscak et al., 1990). Although most pathogens are found in blackwater, greywater commonly harbors small amounts of pathogenic viruses, bacteria, and protozoa and during illness may reach very high levels due to cleansing activity. Because of their potential danger toward humans, pathogens are of the greatest concern in water reuse applications. The main health concern is the small amounts of fecal material present which could contain pathogens. According to Enferadi (California State

Board of Health), "testing found that the common disease bacteria in fecal matter survived and usually multiplied in the greywater systems" (Kane, 1981). It has been reported that one-tenth of a gram of fecal material can contaminate a water system (Kane, 1981). This shows that before greywater is used for irrigation purposes it must undergo some type of treatment. The pathogens present are separated into three categories: viruses, bacteria, and protozoa.

Bacteria can be pathogenic, but, most bacteria are not harmful. In fact, bacteria are necessary in wastewater treatment to degrade pollutants. There are only a few pathogenic bacteria found in wastewater. Coliform and streptococci bacteria, which are frequently measured and reported, are termed "indicator organisms" because they indicate pollution is present. The presence of coliforms and streptococci in greywater suggests there is pollution in the water, however it does not offer information on whether pathogens are present. Fecal coliform is a better indicator of pathogenic pollution in water than total coliform. Table 4 shows the bacteriological characteristics of greywater.

Table 4. Bacteriological Characteristics of Greywater

Water Source	Organism	Number of Samples	Average organisms per liter
Clothes washing	Total coliforms	41	2,150
	Fecal coliforms	41	1,070
	Fecal streptococci	41	770
Bathing	Total coliforms	32	18,100
	Fecal coliforms	32	12,100
	Fecal streptococci	32	3,260

Adapted from: Wilson, A. (1995). "Using Greywater for Landscape Irrigation." *Environmental Building News*, 4(2), 10.

The information in the table suggests bathing produces more microbials than clothes washing. The assumption that more microbials are produced when bathing than when washing clothes is dependent on the household. For example, if baby diapers are washed there is potentially more microbials in the clothes washing water.

There are only a few protozoa that are considered pathogens. Most protozoan infections are in the form of gastrointestinal disorders (Peavy et al., 1985). The most common is Giardia lamblia. Giardia can be transmitted from any mammal and is commonly contracted when a person drinks water out of a natural stream or comes in contact with feces from an infected human. Protozoa form cysts which are hard to treat, but filtration will generally remove them.

The available studies performed on greywater indicate that the application of greywater on soil is an effective treatment method. One of these studies is the "Greywater Pilot Project Final Report." This study was performed by the Los Angeles Department of Water Reclamation and was the first comprehensive study on the safety aspects of greywater application for irrigation. This study showed that there were no potential health effects from using greywater carefully through subsurface irrigation, if the greywater was not applied within 5 feet of the groundwater (Ludwig, 1996a). Another study which was included in Art Ludwig's book, <u>Builder's Greywater Guide</u> was entitled "Movement of biological and biochemical contamination in soil and groundwater." This study was related to the disposal of nearly 100% fecal matter in soil. The study concluded that "when contamination does not enter the groundwater, there is practically no danger of contaminating water supplies." This study also came to the conclusion that, "In homogeneous soil the chance of ground-water pollution is virtually nil if the bottom of a latrine is more than 5 ft above the ground-water table." A perfectly homogeneous soil is not possible, but, this study does help show that greywater, which only has a small concentration of fecal matter is not likely to contaminate groundwater systems unless it is fed directly into the groundwater. Because greywater is known to have small amounts of microbials in it, the first concern that needs to be addressed in the design of a greywater irrigation system is that all safety considerations are met. According to Art Ludwig, in his book, Create an Oasis with Greywater (1996b), greywater needs to be managed with adherence to two safety principles:

1. Greywater must pass slowly through healthy topsoil for natural purification to occur
2. Design so that there is no contact before purification

It has been shown that wastewater is effectively purified of pathogens in the top layers of biologically active soil (Ludwig, 1996b). Greywater treatment can bring the wastewater to levels which are safe to apply to soil, and then the natural soil ecosystem will complete the treatment.

RESIDENTIAL GREYWATER RECYCLING SYSTEMS

A residential greywater treatment system can be installed in a home so that there is minimal impact on lifestyle (Karpiscak et al., 1990). The household setup remains the same, only the pipes below the house are diverted to an on-site treatment unit where the treated water can be pumped directly to a drip irrigation system.

The site characteristics also determine what kind of greywater treatment and distribution system should be used and how it should be designed. Site characteristics including: the soil variation, depth to groundwater, climatic data, intended use of water, amount of water to be applied to the soil, and the proximity to any water sources and structures, must be investigated before any design is initiated.

According to the Sustainable Building Sourcebook (1997) the following factors should be taken into consideration: the size of the lot, topography, the soil texture and structure, the depth of the soil layers, the soil drainage and flooding characteristics, and the permeability of the soil. The lot size should be large enough to allow for an irrigation system plus the required minimum setback distances from neighbors. The Sustainable Building Sourcebook (1997) suggests that as a rule of thumb, lots be at least one-half acre. The lots should have a grade of less than 15%. The California greywater law requires the grade of the lot to be less than 6.67% (Ludwig, 1996a). The texture and structure of soil which functions best is a sandy loam. Clayey soils are the most difficult to deal with because they do not allow the water to percolate through the soil. The depth of the soil layers plays an important role in estimating drainage. Different soils act differently during irrigation, and it is important to know where one type of soil ends and where another soil begins.

If greywater is intended to be the only water used for irrigation, the system must be designed to incorporate that, and only certain types of plants should be grown with greywater. These typically are the hardy varieties, which include xeriscape plants with reduced water requirements. There is some disagreement among designers and policy makers regarding greywater irrigation of food plants. Enferadi (California State Board of Health) suggested that recycled greywater should only be used on decorative plants because what is absorbed by root systems is still unknown (Kane, 1981). This appeared to be a major concern in the late 1970s and early 1980s, but more recent investigations suggest that using the water on plants used for food is not a concern as long as the greywater has been sufficiently treated. The greywater should be used on the hardier varieties of landscape plants while clearwater, such as rain catchment should be used on food plants and delicate varieties. The quality of the treated effluent will determine where and on what plants the water can be used. The New Mexico Guidelines suggest that greywater can be used to irrigate the plants in Table 5.

Table 5. Plants which can be irrigated and volumes of greywater needed

Plant	Greywater (gal./week)
Fruit trees	75
Ornamental trees and shrubs	10
Large shade tree	50
Flowers and other ornamental ground cover	varies
Lawns	varies

It should be noted that citrus trees may be adversely affected by greywater and are not included in the fruit trees above. The New Mexico Guidelines suggest that greywater should not be used to irrigate shade and acid loving plants, such as the ones shown in Table 6.

Table 6. Plants which should not be irrigated with greywater

Rhododendrons	Azaleas	Ferns	Bleeding Hearts
Violets	Foxgloves	Oxalis	Impatiens
Gardenias	Primroses	Hydrangeas	Primroses
Begonias	Camellias	Philodendrons	

Adapted from: Ludwig, A., (1996b). "Creating an Oasis With Greywater."

DESIGN OF GREYWATER RECYCLE SYSTEMS

This section reviews a number of greywater treatment alternatives. The greywater systems consist of greywater fixtures that feed a septic tank which feeds a subsurface irrigation and/or disposal system. Between the plumbing of the greywater fixtures and the greywater tank, there should be a valve to allow diverting of the greywater flow from the irrigation system to the regular septic tank system during winter and during periods of heavy rain. After the greywater tank there should be distribution valves which allow the routing of irrigation water, either by gravity or by pump, to various zones. There should be at least two irrigation zones to allow the soil to drain and breathe. The beneficial bacteria prefer soils that are well aerated. Thus, the overall system consists of:

Greywater Plumbing Fixtures + Switching Valve + Greywater Tank + Distribution Valve + Irrigation Disposal Field

Greywater Tanks – All greywater is drained into the greywater tank. From the greywater tank, the greywater may drain directly to the landscape, or to further treatment depending on irrigation system needs. The greywater tank will require a vent, either an above-roof vent or one equipped with an activated carbon filter. The greywater tank must be the same size as a regular septic tank. All setbacks as defined by the state must be met.

Drainfields and Irrigation Areas

Greywater irrigation systems are near the surface to keep the water in the plant root zone as long as possible. The gravity flow systems are best for deep rooted plants like trees and certain shrubs. The irrigation systems come in many shapes and sizes:

mulched watering moats
gravel mini-leach pits with upside-down flower pots as inlets
rectangular shallow drainfields for long reaches
pumped irrigation systems
special sand drainfields

Mulched watering moats – When the amount of greywater is minimal, a pair of heavily mulched moats around two trees may be the best solution. An eighteen-inch deep ditch is dug beneath the outside edge of the tree's foliage, that is, at the dripline. A permanent or dedicated hose or pipe brings water to the moat. Benefits of this system include: inexpensive, easy installation, easy operation, easy maintenance. Disadvantages include: little operational flexibility, restricted to flat areas, biweekly or monthly maintenance, inefficient use of the greywater, greywater is not secure from pets and wildlife. The design and construction details of this system are available from the NMED (1997).

Mini-leach pits – This is a simple irrigation system. It can be constructed by placing a gravel pocket in the vicinity of the plant to be watered. An upside-down flower pot, or any other hollow container, with an emitter inside is placed over the gravel pocket. This system has a number of advantages, which include: simple construction, the inverted flower pot emitter prevents the plant roots from growing back into the irrigation lines and plugging them, efficiency and uniformity of water use are better than that of the moat system, and it can be used on shrubs and trees. The limitations of this system include: the time required to balance and adjust the flows, above ground piping is unsightly, and the system is susceptible to some clogging. The design and construction details of this system are available from NMED (1997).

Shallow Leachfields – A greywater shallow leachfield would be much the same as a normal septic tank leach field except that it is closer to the surface to allow the water to reach the plant root zone. The beds can be smaller in size than the normal leachfield due to the smaller flow. Irrigation efficiencies for these systems are rated very low. Other types of absorption systems include shallow trench and a shallow mound. The shallow trench involves pumping the greywater into a trench approximately 10-12 inches deep. The landscape that is being irrigated is placed in the trench. A shallow mound can also be used. This is simply an elevated absorption field, primarily used for unsuitable soils. This system has a number of advantages, including: it is simple to install, doesn't plug easily, is easy to maintain, and is ideally suited to shrubs and trees. Disadvantages include: it is awkward to install in existing landscape, it is an inefficient use of greywater, it waters a small area, plants at the beginning of the trench get more water, it must be installed level, and it is not suitable for ground cover and lawns. The design and construction details of this system are available from NMED (1997).

Irrigation – There are two types of irrigation systems, conventional and drip irrigation. A conventional sprinkler system is efficient, and easily controlled. However, due to code requirements and the intrinsic properties of greywater, conventional sprinkler systems should not be used for greywater irrigation unless the effluent water meets high water treatment standards. Specifically, the greywater must be disinfected and large solids removed. It is not economically feasible to have a complete secondary wastewater treatment system in a residential home. Note that disinfection usually includes the use of chlorine which is toxic to plants.

Drip irrigation involves a series of plastic tubing with a number of small devices (emitters) installed which control the flow of water to a small trickle. It is a near surface irrigation system usually covered by 9 inches of dirt or mulch. These systems are the most efficient way to water plants and the best way to water spreading plants; the water can be controlled and dispersed evenly. However, the emitters have tiny holes to regulate the water flow. Grease, oils, lint, and particles present in greywater can plug these holes quickly. Because of this plugging problem, drip irrigation should only be conducted after filtration. Drip irrigation systems can reach irrigation water use efficiencies of 80% (Ludwig, 1996b).

Sand filtration is one of the most common types of treatment systems available. Sand filtration involves passing the water through a stationary media. A filter can be made from a wide variety of material such as sand, anthracite, and ag-lime. Water enters the sand bed from the top where it percolates down either by pressure or by gravity. Sand filters remove many pathogenic organisms, but do not eliminate them so the effluent from a sand filter must be applied subsurface. One problem with any type of filter is that over time the trapped suspended solids will clog the filter and it will not work effectively. To prevent this, the filter must be backwashed periodically. The backwashing process involves running clean water backwards through the sand, flushing the system clean. In a slow sand filter, to prevent clogging the top layer of sand is periodically removed and replaced with new sand.

The "Casa del Agua" home in Tucson and the "Desert House" in Phoenix both use a sand filtration system to treat the greywater before it is used in a drip irrigation system. Commercial filtration systems are available, such as the "Automated Greywater to Drip System" developed by Agwa Systems Inc. This is a prefabricated sand filter with an automatic backwashing system that backwashes the sand once every two months. According to Ludwig (1996b), "they are expensive and consume power, but they deliver on their promise of hands-off operation and have uniquely high irrigation efficiency." There are other automated filtration systems suppliers, such as "Aquabank," "Clivis Multrum Inc.," and "Rewater Systems Inc." to name a few.

Drip irrigation is the most efficient way to irrigate. This system promotes the healthiest plants, the best growth, the best blooms and the highest yields. Other benefits include: it spreads the greywater over the largest area, has the most control, allows slow percolation of the water into the soil, allows irrigation on slopes and in clay soils, applies greywater close to the surface for the most efficient use of organics and nutrients, and can be operated automatically. Some of the disadvantages include: complicated hardware, more costly than the other techniques, prone to clogging, requires more maintenance, higher energy use, and cannot be used as a gravity system. The design and construction details of this system are available from NMED (1997).

CONSTRUCTED WETLANDS SYSTEMS

An alternative greywater treatment system is the constructed wetland. A constructed wetlands system consists of pretreatment for removal of solids, followed by a lined sand or gravel bed with plants in the bed to treat the water. Wetlands use the wastewater as a food to support vegetation such as Canna lilies, iris, and cattails (Sustainable Building Sourcebook, 1997). Most commonly, plants are planted directly into the rocks or gravel media and no soil is used in this system. Wetlands provide simple effective treatment and are getting increased attention for use on treatment of wastewater (blackwater).

The Earthship homes use a constructed wetlands treatment unit for the greywater treatment system. The system treats all greywater from the home through a large treatment system that usually extends the length of the front of the home. The treatment system is located indoors along the south side of the home where most windows are located. The unit is comprised of a grease trap and particle filter, a treatment planter which is composed of rocks and pumice planted with vegetation, and a peat moss filter (Reynolds, 1996).

The Campus for Appropriate Technology located at Humbolt University in California is experimenting with a greywater treatment marsh. The system treats water from sinks and showers. Greywater enters a primary treatment tank, which is used to settle out large particles. The marsh is comprised of three chambers filled with gravel. Each chamber is planted with vegetation. The greywater is applied at the top of the chamber at one end and it percolates down through the soil the length of the chamber. The water is removed from the bottom of that chamber and enters the top of the next chamber so that oxygenation of the water will occur. The settling tanks must be emptied approximately three times per year, and the vegetation must be cut back. The treated water is used for irrigation (Campus for Appropriate Technology, 1997).

STATE REGULATIONS

Greywater is regulated separately from blackwater in fifteen states. The majority of the state regulations allow the flow of a greywater system to be decreased if greywater is treated separately from blackwater. Table 7 includes these states and the requirements regarding greywater.

Table 7. State Regulations Regarding Greywater

State	Source	Flow	Tank Specifications	Requirements
Arizona	all drains	reduced by 40% of total septic	septic	septic tank to leach field; Permit may be obtained to have any approved greywater treatment systems in certain counties
California	No garbage disposal	Showers, bathtubs and washbasins = 25 GPD/ occupant, Laundry = 15 GPD/occupant	Regulated by Administrative Authority	Follow California Plumbing Code Appendix J Regulations
Colorado				Same as minimum design for septic system
Connecticut		1/2 capacity		Septic tank to leach field
Florida				Approval of individual systems by state Health Office
Hawaii		150 gal/day/BR	>600 gallons	Uses: sand filter/adsorption trenches and beds/mounds/seepage pits
Kentucky	laundry only	15% reduction: soil groups I-III, No reduction: soil group IV		Trench > 100 ft^2 of adsorption area for a 2 bedroom home + 50 ft^2 per bedroom
Minnesota	no garbage grinders		≤ 2 BR = 300 gal 3-4 BR = 500 gal 5-6 BR = 750 gal 7-9 BR = 1000	Plumbing: 2 in pipe with no openings or connections. Should be >2 in. Same as septic tank
Montana				Same as all wastewater
New Jersey		75% of blackwater		Case by case approval

New York		75 gal/day/BR		Same as wastewater
Oregon	all			Disposed by discharge to: 1) existing on-site system 2) new on-site system with a soil absorption facility 2/3 normal size 3) public sewage 4) disposal sump and trench
South Dakota		minimum 25 gal/day/person	3 days retention time or approval on case by case basis	Greywater recycle must be in accordance with specific distances. Reuse in: toilet use/absorption fields/ mounds/seepage pits/irrigation of lawns and non-food plants (upon receipt of percolation tests)
Texas		40-60% of total water conserving fixtures: 10% additional reduction		Texas Department of Health registers: subsurface adsorption, evapotranspiraton, and subsurface irrigation. Anything else must be designed by a registered professional engineer
Wyoming		33% reduction		same as septic

AA = Administrative Authority
BR = Bedroom
gal = gallon
GPD = gallons per day

Source: National Smallflows Clearinghouse, (1995).

Even though several of these states include greywater in their regulations, in most states it is not intended to be used for irrigation. Many of these regulations were made to accommodate split waste systems that use composting toilets.

CONCLUSIONS

Greywater can be used for irrigation with appropriate pre-treatment using systems such as septic tanks, sand filtration, or constructed wetlands systems. After treatment with one of these systems, it then can be used for the subsurface irrigation of landscape plants. Greywater reuse not only has been shown to be an effective method of disposing greywater, but it also creates another alternative for irrigation. Greywater systems are becoming more popular around the United States due to water shortages and pollution of aquifers, and because of these pressures, regulations are beginning to change. California was the first state to institute change statewide. However, other states, including New Mexico, are currently preparing their final regulations.

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ENHANCING NITROGEN REMOVAL IN SUBMERGED SURFACE FLOW CONSTRUCTED WETLAND SYSTEMS

W. Zachritz II[90], A. Hanson[91], and B. Thomson[92]

Wetlands wastewater treatment systems or "treatment wetlands" are either free water surface (FWS) or submerged surface flow (SSF) systems. Both types of systems use a combination of natural processes to effect wastewater treatment. While the construction of these wetland systems does create the appearance of "wetland habitat," the primary objective is wastewater treatment. SSF constructed wetlands systems use a bed of soil, gravel or rock as a substrate or media for the growth of rooted, emergent wetland plants such as cattails (Typha) or bulrush (Scirpus). Normally, several species of plants are growing in the wetland system. Wastewater flows horizontally through the bed media contacting a mixture of aerobic, anaerobic, and facultative microbes living in association with the substrate and plant roots (Kadlec and Knight, 1996) as shown in Figure 1. The rock in these systems ranges in size from 6 to 150 mm (0.25 to 6 in) with 13 to 76 mm (0.5 to 2 in) typical (Reed and Brown, 1992), and a typical bed depth of 0.5 - 0.7 m (1.5 – 2.0 ft). Many systems are designed with a cap of smaller "pea gravel" to allow for easier propagation of newly introduced plants. The water level in these systems is maintained below the rock surface by an adjustable stand pipe located at the outlet sump.

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[90] Director, Environmental Systems Division, Southwest Technology Development Institute at New Mexico State University, Las Cruces, New Mexico 88003

[91] Associate Professor, Civil, Agricultural, and Geological Engineering Department, New Mexico State University, Las Cruces, New Mexico 88003

[92] Professor, Civil Engineering Department, University of New Mexico, Albuquerque, New Mexico, 87131

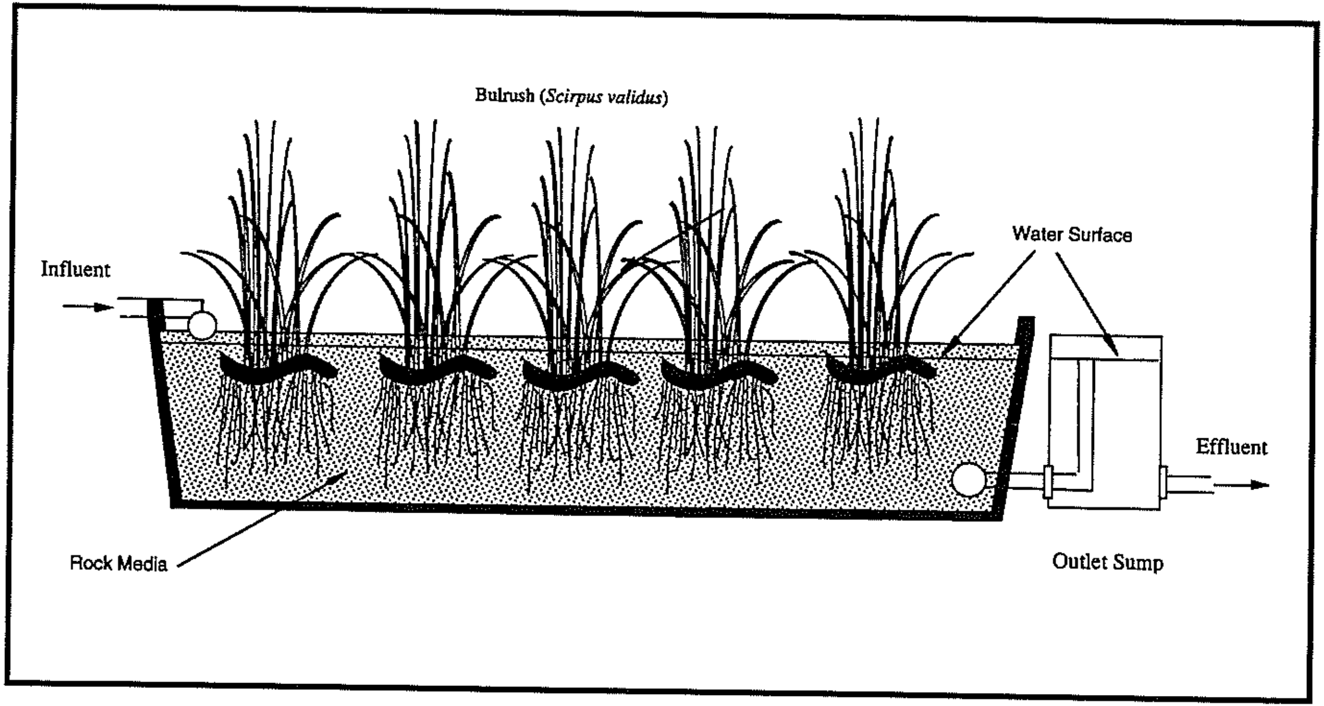

Figure 1. Side View a SSF Constructed Wetlands System with Effluent Sump and Water Level Stand Pipe.

Length to width ratios, which affects the reactor hydraulics of the system, vary from 10:1 to 1:1 with a typical ratio of 2:1 (USEPA, 1993a). These systems (Figure 2) require pretreatment such as facultative or aerated lagoons or simple sedimentation (septic tanks) before the wastewater enters the wetland cell. Pretreatment is critical to prevent excessive loading of suspended solids (TSS) that might cause clogging of the interstitial rock spaces resulting in possible "ponding" or system short circuiting of the wastewater flow. Currently wetlands are used primarily to treat municipal wastewater although they have been used to treat a variety of industrial wastewaters and water from runoff events (Kadlec and Knight, 1996). Wetlands have reportedly been effective for reducing high levels of biochemical oxygen demand

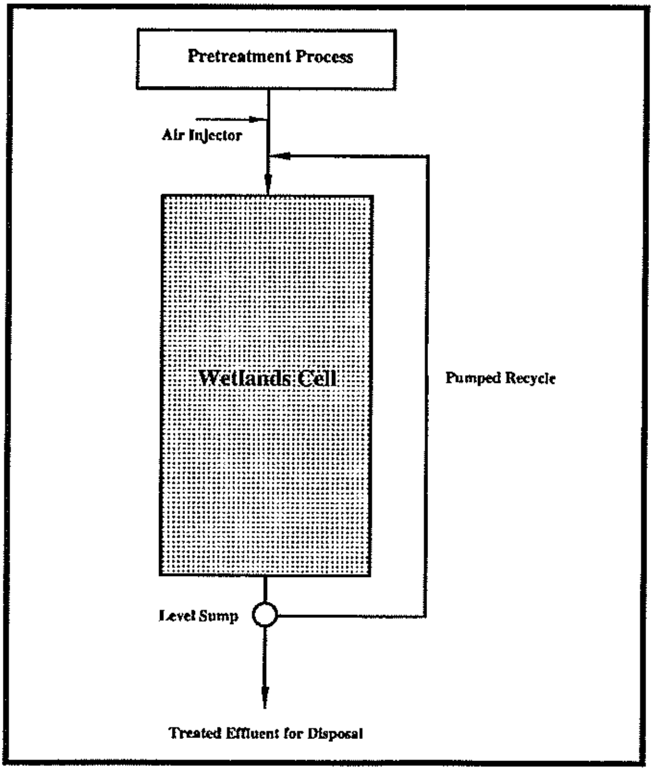

Figure 2. Layout of a Conventional SSF Wetlands System with Provision for Flow Recycle.

(BOD_5), TSS, and nitrogen, as well as significant reduction in the levels of trace metals, trace organic and pathogens in a number of applications (Reed et al., 1996).

There are probably more than 10,000 operating systems in the U.S. covering every region and ranging in size from small home systems to large municipal facilities with daily flows of over 3 million gallons. In recent years, many of these systems must not only meet standards for BOD_5 and TSS, but are required to meet new, more stringent discharge standards for nutrients such as phosphorus, ammonia, nitrate and total nitrogen. Thus, new discharge standards were imposed after systems had been constructed and were operational. In a study conducted on over 20 constructed wetland systems operating in the U.S., most of these systems failed to meet National Pollution Discharge Elimination System (NPDES) limits for NH_3-N (Reed and Brown, 1992). Nationally, municipal constructed wetlands systems appear to have a poor record for nitrogen removal in general and ammonia treatment in particular (Askew, Hines and Reed, 1994).

New Mexico has over 40 operating wetland systems of various designs, most of which were constructed in the past five years. Most of these facilities do not discharge to surface waters, but to groundwater and are permitted by New Mexico Environment Department's (NMED) Groundwater Bureau. Recent studies on SSF wetland systems operating in New Mexico (Thomson et al., 1996) indicated that many of these systems may not meet performance expectations for BOD_5, TSS, ammonia, nitrate and total nitrogen. This indicates that many of the systems operating may be exceeding the limitations for effluent discharges to the subsurface of 10 mg/L TN (NMWQCC 3105A). There is growing concern that these low-cost and easy to operate systems may not be acceptable to regulators without some changes in the existing design approach. The purpose of this paper is to review some of the aspects of apparent SSF wetland system failure and present general modifications to improve future performance of these systems with an emphasis on nitrogen removal.

NITROGEN REMOVAL

Nitrogen can occur as both organic nitrogen and urea nitrogen in raw wastewaters (Metcalf and Eddy, Inc., 1991). Organic nitrogen is contained in all organic materials found in wastewaters including feces and kitchen wastes and undergoes the microbially driven process of ammonification to release ammonia to the wastewater. Urea, the major component of urine, hydrolyzes rapidly to form ammonia and carbon dioxide in the presence of microorganisms containing the enzyme urease as shown in Equation 1. The breakdown of urea to form ammonia may take just a few minutes while the release of ammonia from organic nitrogen sources may take several days or months. Thus, the nitrogen in most raw wastes is a combination of these

Urease

$$H_2NCOH_2N + H_2O \rightarrow CO_2 + 2NH_3 \tag{1}$$

Once ammonia is present it can be removed biologically from wastewater via the process of nitrification/denitrification. Nitrification is a strictly aerobic, two-step microbial process, which converts ammonia to nitrite and then to nitrate as shown in equations 2 and 3. *Nitrosomonas* oxidizes ammonia to the intermediate product nitrite, and *Nitrobacter* converts nitrite to nitrate. Stoichiometrically it takes

Nitrosomonas

$$NH_4^+ + 1.5\ 0_2 + 2\ HC0_3^- \rightarrow N0_2^- + 2\ H_2C0_3 + H_20 \tag{2}$$

Nitrobacter

$$NO_2^- + 0.5\ O_2 \rightarrow NO_3^- \tag{3}$$

4.3 mg/L of O_2 and 8.64 mg/L (as $CaCO_3$) of alkalinity to convert 1 mg/L of ammonia to nitrate (as N) (Kadlec and Knight, 1996). If oxygen, alkalinity or both are limiting, the reaction will not proceed. In addition, nitrification can be limited by temperature, salinity, presence of a carbon source, and pH (USEPA, 1993b). Nitrifiers grow slowly and rates of ammonia conversion are lower than the rate of organic material conversion.

The amount of organic material in waters is measured by the BOD test that determines the oxygen demand of a given sample in mg/L O_2. The degradation of organic material competes with the nitrifying bacteria for oxygen and rates of nitrification will be inhibited by the presence of quantities of BOD_5 above 20 mg/L. Consortia of microorganism reduce organic matter according to equation 4. Organic material can occur as both dissolved and degradable particulate material,

$$\underset{\text{(bacteria)}}{\text{COHNS}} + O_2 + \text{nutrients} \rightarrow C0_2 + NH_3 + \underset{\text{(new bacteria matter)}}{C_5H_7N0_2} + \text{other end products} \quad (4)$$

which can exert a demand for oxygen in a system. The degradation of TSS is generally assumed to exert about 0.5 mg of BOD_5 for each mg of TSS degraded. It is critical to the nitrification process that BOD_5 be reduced to concentrations that will not inhibit the growth of nitrifiers and that sufficient oxygen is present to allow the nitrification process to proceed to the end products.

Denitrification results in the removal of nitrate by conversion of nitrogen to nitrogen gas accomplished under anoxic conditions by a diverse group of facultative bacteria (Metcalf and Eddy, Inc., 1991). Dissimilitory nitrate reduction is a two-step process with the first step involving the conversion of nitrate to nitrite as shown in Equation 5. The second step is the production of nitric oxide, nitrous oxide, and then nitrogen gas as in Equation 6. The availability of a carbon source is

$$NO_3^- + 0.33\ CH_3OH \rightarrow NO_2^- + 0.67\ H_2O \quad (5)$$

$$NO_2^- + 0.5\ CH_3OH \rightarrow 0.5\ N_2 + 0.5\ CO_2 + 0.67\ H_2O + OH^- \quad (6)$$

critical for completion of this process. The carbon source is oxidized and donates electrons while nitrate gains electrons and is reduced to nitrogen gas and released to the atmosphere. Many different compounds can serve as a carbon source, but not all compounds result in an efficient conversion of nitrate to nitrogen gas.

In SSF wetland systems, nitrification and denitrification are reported to be the major pathways for ammonia removal (White 1995). Plant uptake of nitrogen is estimated to be less than 20 percent of the total nitrogen removed by SSF wetland systems. The process of nitrification is optimal when DO is in the range of 2 to 7 mg/L; however, some nitrification will occur at DO concentrations down to 0.3 mg/L. Most SSF wetlands systems operating in New Mexico have effluent DO levels less than 1 mg/L (Thomson et al., 1996), indicating highly decreased nitrification rates. This decrease is of concern because nitrification is considered the rate-limiting step for nitrogen removal in constructed wetland systems (White 1995).

The removal of nitrate in SSF constructed wetlands appears to occur rapidly once ammonia is converted to nitrate. Gersberg et al. (1984) reported efficiencies of 97 percent for total inorganic nitrogen (ammonia and nitrate) and 94 percent for total nitrogen (TN) achieved via denitrification with Methanol. Substituting plant biomass in the form of mulch as the carbon source resulted in the removal of 95 percent total inorganic nitrogen and 89 percent TN at hydraulic loading rates of 8.4 to 12.5 cm/d. Blending primary effluent as the carbon source with the secondary effluent, resulted in removal efficiencies as high as 79 percent for total inorganic carbon and 77 percent TN while maintaining 89 percent rates for BOD_5 and TSS. Other types of carbon-donated materials such as peat have also been effective in the nitrification denitrification process (Lens et al., 1993).

In wetland systems mechanisms for ammonia removal are thought to be a combination nitrification and plant uptake processes, but it is not known how or where these processes occur within the wetland bed. Gallegos (1997) recently developed a technique for examining the microbial processes driving the sequence and mechanisms of electron acceptor utilization SSF constructed wetland system. The results indicated that DO and oxidation reduction potential (ORP) decreased rapidly in the first portion of the wetland bed, caused by the oxidation of entrapped solids, soluble organics, and ammonia. Denitrification also occurred in the same part of the bed, but was rapidly carbon limited. There appeared to be an activity zone in the very front of a wetland reactor bed. In this zone "microenvironments" of bacterial driven activity resulted in the majority of components removed by the system. Removal activity dropped off dramatically through the rest of the bed and only marginal re-aeration (increase of DO and ORP) of the bed was noticed. The sequence of electron transfer activity appeared to indicate that these processes occurred simultaneously in the same bed location rather than sequentially along the length of the bed. The removal of ammonia appears to be oxygen limited even for systems operated at much lower hydraulic residence times (HRT) than conventional designs. This agrees with data and analysis performed by Thomson et al., 1996.

DESIGN ANALYSIS

The design approach for many SSF wetlands is outlined in several reports (Kadlec and Knight 1996; USEPA 1993a; WPCF 1990), and assumes a plug-flow configuration using Equation 7 to describe the removal of BOD_5. This equation incorporates the hydraulic retention time (HRT), water temperature, porosity of the rock media, and a first-order kinetic constant K_T to determine the bed size requirements. K_T is adjusted for temperature affects using equation 8 with a typical

$$C_e/C_o = e^{(-K_T \times \mathrm{HRT} \times \emptyset)} \tag{7}$$

where;

C_e = effluent BOD_5, mg/L;
C_o = influent BOD_5, mg/L;
$\emptyset$ = rock porosity, %;
K_T = temperature dependent first order reaction rate constant, days $^{-1}$; and
HRT = hydraulic residence time, days.

value of 0.811 at 20°C. K_T value actually estimates the aerial transfer of oxygen to a 2-ft deep SSF bed for removal of BOD_5 in the system. (Metcalf and Eddy, Inc. 1991; WPCF 1990). Estimated oxygen transfer rates through the surface of SSF wetlands planted with emergent plants range from 5 to 45 gm O_2/m^2-day with average values assumed

$$K_T = K_{20}\,(1.1)^{(T-20)} \tag{8}$$

where;

T = system temperature °C,
K_{20} =first order reaction rate constant at 20°C, days $^{-1}$.

to be 20 gm O_2/m^2-day (USEPA 1988). These transfer rates are assumed to be a combination of simple diffusion and active transport through the roots of the emergent plants. The K_T value assumes that all degradation of BOD_5 occur through an aerobic pathway. It is critical to this design approach that oxygen assumptions for the K_T values are not exceeded or significant shortfalls of oxygen will occur and poor system performance will result (Metcalf and Eddy, Inc. 1993).

The removal of suspended material (TSS) in SSF systems occurs rapidly in the first part of the wetland bed and is assumed to be a process of sedimentation, entrapment, and filtration (Zachritz and Fuller 1993). No equations are available for predicting or designing for the removal of suspended solids, but most systems appear to provide good removal of TSS. TSS does impart an oxygen demand to the system as the solids are trapped and the degradable fraction is oxidized. TSS also contributes to the TN of the system because the solids contain organic nitrogen that can result in the release of ammonia into the wastewater. Additionally the characteristics of the solids in the influent can be quite different from the solids discharged in the effluent.

Equations for the prediction of nitrogen removal in SSF systems have historically been weak and are based primarily on linear regression analyses that lack temperature correlation parameters (WPCF 1990).

Recent investigators (Kadlec and Knight 1996; Reed et al., 1996) have suggested several equations, the most notable is a version similar to the plug-flow equation presented above (Kemp and George 1997) with a K_{20} value of 0.411 for the removal of ammonia. Reed et al., (1996) has suggested a value for K_T of 0.467 for this same model. The value represents the aerial transfer of oxygen sufficient to complete the oxidation of ammonia to nitrate.

Based on the design approach outlined in Metcalf and Eddy, Inc. (1996) and data from Thomson et al., (1996), the wastewater characteristics assumed for design and determined from samples for SSF systems in New Mexico are presented in Table 1. Examination of the data indicate that assumed design values for BOD_5 are 26.1 percent lower than actual average influent values determined by Thomson et al., (1996), while ammonia concentrations are about the same. This suggests that the systems designed and operated in New Mexico have much higher BOD than loading assumed in typical design approaches. In addition, the assumed design BOD_5 waste strength constitutes about 40 percent of the total oxygen demand, while ammonia nitrogen and TSS constitute 52 and 8 percent of the demand, respectively. Thus, conversion of ammonia actually requires more oxygen than just simple

Table 1. Observed and Assumed Wastewater Characteristics and Resulting Oxygen Demand for SSF Wetland Systems in New Mexico.

Parameter	Design Influent mg/L	O_2 Demand % of total	Observed Influent[1] mg/L	O_2 Demand % of total	Design Effluent mg/L	Observed Effluent[1]
BOD_5	150	40	203	44	12	91.5
TSS	50	8	152	17	10	74.5
NH_3-N	45	52	42.2	39	12	26.6
NO_3-N	2	NA	0.05	NA	2	1.8
TN	50	NA	56.9	NA	15	38.1

1 Data from Thomson, Boivin, and Gallegos-White, 1996

BOD removal. Furthermore, BOD_5, and degradable TSS must be removed below concentrations (~10-20 mg/L) that will allow nitrification to proceed, indicating further potential for inhibition of the nitrification process. The actual measured waste data indicate a higher percent of oxygen demand attributed to TSS and BOD_5, again suggesting that nitrogen removal will be limited.

MODEL SIMULATIONS

A simulation of a SSF wetlands system using the design equations with a HRT of 4.5 days, and K_{20} values for ammonia and BOD_5 removal of 0.411 and 0.867, respectively (Metcalf and Eddy, Inc. 1996; Kemp and George 1997) was conducted in the modeling environment Extend ™. Inputs were generated using a simplified Monte Carlo approach to statistically vary influent concentrations. Simulations were run for 365 days with a 1-day time step. The first simulation was run with a constant 20°C temperature as shown in Figure 3. At an input BOD concentration of 150 mg/L, the model predicts effluent BOD concentrations below 20 mg/L. Increasing influent BOD_5 from 150 mg/L to 200 mg/L results in an increase in effluent concentrations of about 10 percent to about 23 mg/L. The impact on ammonia removal using the design equations presented in Figure 4 indicates that increasing BOD concentration did not affect ammonia removal. Thus, the present design approach does not compensate for increased BOD loading that should inhibit nitrogen removal. The data from these simulations and Thomson et al., (1996) indicate that the kinetic values used in the design of systems in New Mexico do not appear to be adequate. Calculated aerial oxygen transfer for observed data and assumed design values were 9.19 and 13.92 gm O_2/m^2-day, respectively. The system performance based on observed data was 33 percent less in terms of oxygen transferred than the assumed design conditions and parameters. While all this data are within the reported ranges for oxygen transfer (Kadlec and Knight 1997), these assumed design conditions appear to be inadequate for use in New Mexico systems. The reasons are not clear from the data, but

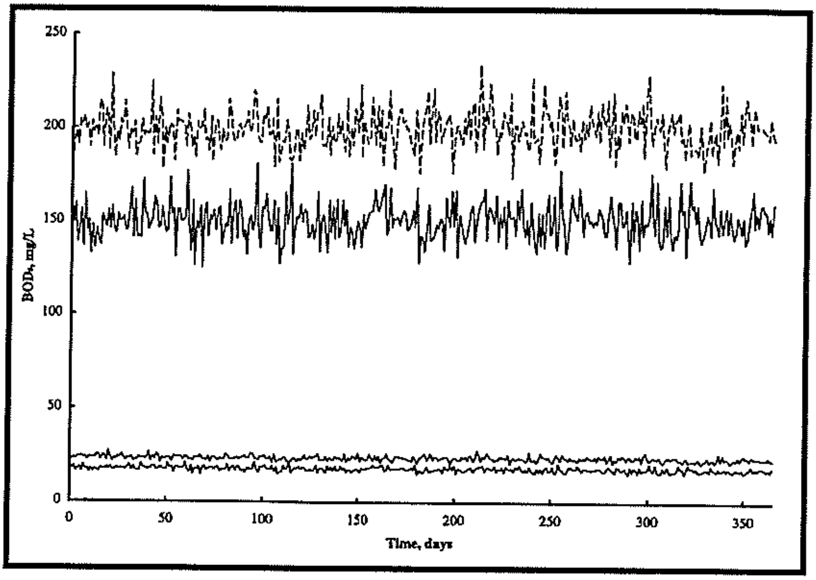

Figure 3. Monte Carlo Model Results of Influent and Effluent BOD_5 Simulations Using a Plug Flow Model.

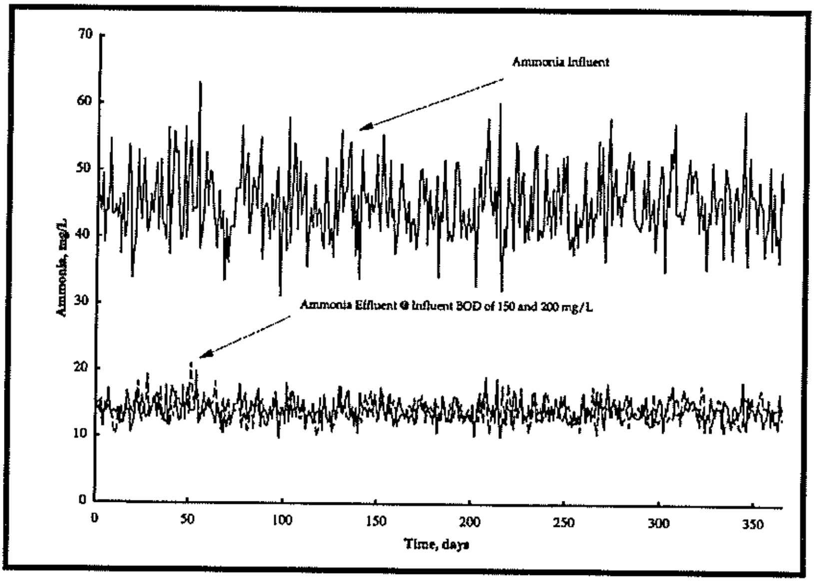

Figure 4. Effect of Varying BOD Influent Concentrations on Plug-Flow Model Predicted Effluent Ammonia Nitrogen Concentrations.

higher altitudes may hinder oxygen availability and transfer in some systems and thus alter the fundamental conditions affecting the design process.

The data used to develop many of the kinetic parameters critical to the design of SSF system have been developed from national databases. Much of the data are from systems, which incorporate upstream treatment processes such as lagoons or activated sludge treatment plants. These treatment processes tend to provide a greater degree of treatment than the New Mexico systems are receiving and thus, reduce the actual influent BOD and K values used to determine both nitrogen and BOD_5 removal. The kinetic values developed for nitrogen removal by Kemp and George (1997) were tested in systems with average BOD influent concentrations of only 50 mg/L, but systems operating in New Mexico have BOD influent concentrations nearly four times greater than the systems used to develop the nitrogen design information.

Simulations using the design equations in a Monte Carlo format for ammonia and BOD_5 inputs run with water temperature variation for seasonal changes are shown in figures 5 and 6. The design equations in this case show excellent performance with almost zero effluent BOD_5 concentrations during the warmer months, but during colder months with temperatures near 8 °C, BOD effluent values increased to about 50 mg/L. Nitrogen removal shown in Figure 6 also shows greater removal in summer than winter months with the lowest values dropping below 10 mg/L as N. Thus, the design equations when coupled to temperature corrections indicate excellent performance for this example SSF wetlands system for most of the year for BOD and ammonia. This model predicted performance for ammonia is questionable since the hypothetical system has a 4.5 day detention time and is not designed to remove nitrogen.

Field data does agree with the design example presented. It is apparent that assumptions for the use of these systems in New Mexico needs

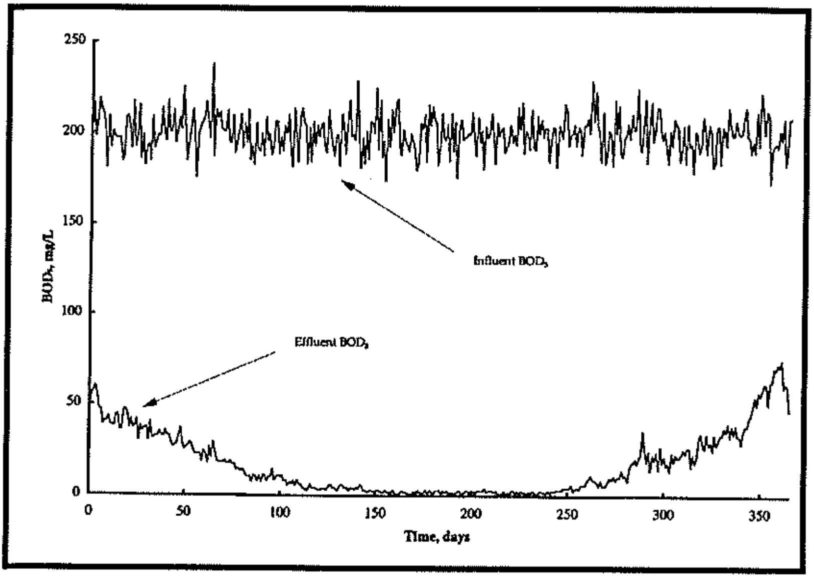

Figure 5. Model Simulated Influent and Effluent BOD Data for a Hypothetical SSF Wetlands System.

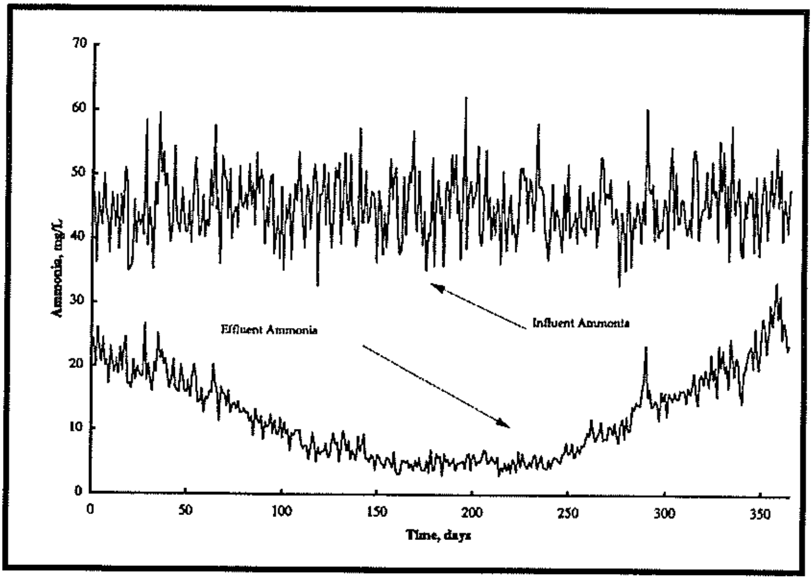

Figure 6. Model Simulated Influent and Effluent Ammonia Nitrogen Data for a Hypothetical SSF Wetlands System.

to be re-evaluated and new concepts for design approaches developed. SSF wetland systems offer advantages such as low maintenance cost and low operator training requirements that small communities find highly attractive. Additionally, for many pollutants such as metals and complex organics these systems offer significant advantages in removal efficiencies and costs. But the existing information for kinetic values appropriate for design of systems for BOD_5 and ammonia removal is inadequate. Most SSF wetlands designed and constructed nationally have upstream processes such as aerated and facultative lagoons that provide a higher level of pretreatment for BOD_5 and nitrogen. This results in overall lower values and lighter loads treated by these systems. In New Mexico, with septic tanks or simple sedimentation (no active sludge removal) as the sole pretreatment, higher and more variable loading of wastes are encountered. This appears to produce significant oxygen limitations in many SSF wetland systems and results in lower than expected performance.

Based on our model analysis and data from Thomson et al., (1996), SSF wetland systems would require the addition of about 4.73 gm O_2/m^2-day to provide adequate processing of the typical influent wastes in New Mexico systems. In-bed aeration (Figure 7) such as open areas with diffuse aeration devices (Dupuy 1996), surface agitators, recirculation of effluent through exterior trickling filters (Sikora et al., 1995), reciprocating biofilters (Behrends et al., 1993), aerated ponds, and pretreatment with aerated ponds are all possible approaches. Oxygen solubility is affected by altitude and temperature and the transfer of oxygen is impacted by the depth of water, size of bubbles formed by aeration devices, presence of TSS, the use of air or pure oxygen, and other factors. SSF wetland systems are shallow, typically less than 2 ft in depth, which is not an ideal environment to enhance oxygen transfer. Additionally, treatment may not take place just in one location, but throughout the bed and thus oxygen must be aerially distributed to meet treatment requirements. Trickling filters can provide enhanced nitrification with no need for an additional air

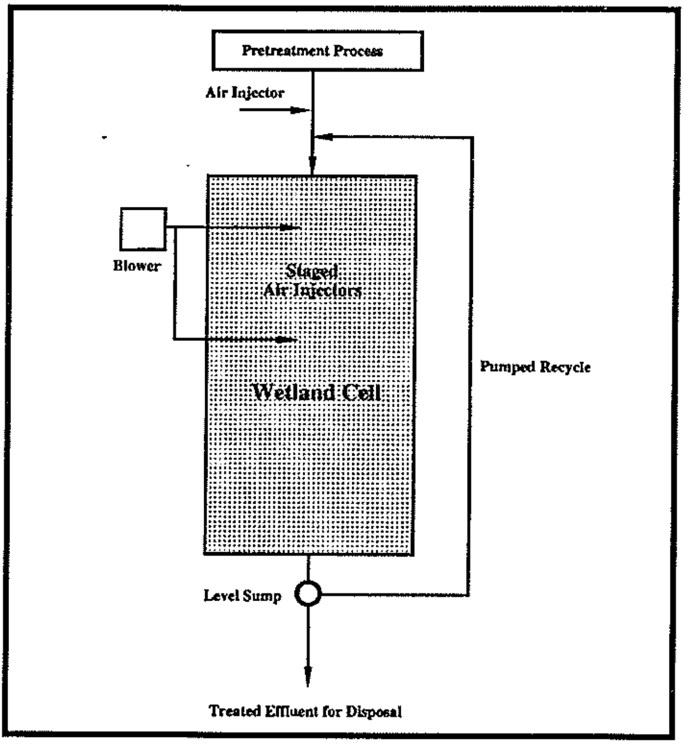

Figure 7. Layout of a SSF Wetlands System with Provision for Flow Recycle and Aeration.

blower, but extra costs are needed for the filter and recirculation rates must be increased as much as 300 percent to achieve good removal. These high rates of recirculation increase costs for pumping, dramatically impact hydraulic loading rates to the wetlands, and alter documented design approaches for SSF systems. Aerated ponds may enhance nitrification, but required an add-on blower, may increase generation of odors and algae, and increase operation costs. In-bed systems such as air lift pumps would also have higher operational costs and require more operator attention, but would not require additional pond or facility space and would minimize the production of nuisance odors while providing enhance nitrification. All of these approaches need to be evaluated and tested to develop design and operational data.

The addition of oxygen must be designed around the constraints of shallow depths and other considerations for retrofitting existing systems, but could open totally new design approaches for new systems. Deeper beds with shorter detention times using air lift pumps or air injection systems could enhance oxygen transfer while decreasing the overall capital costs for the bed and related rock media; in essence, creating a series of sequencing batch reactors optimized to remove the necessary waste components without excessive use of oxygen inputs.

SUMMARY

Development of information and data collected in a systematic way is needed to determine adequate kinetic coefficients for design equations for SSF systems to be used in New Mexico. In addition, examining new ways to add supplemental oxygen needs to be explored and design information developed. Recirculating trickling filters, diffuse aeration, air lift pumps, and staged influent are all possible solutions to the problem of improving system performance. Activated sludge is the standard for design of many secondary wastewater treatment systems in the U.S. and around the world. This process has been under development since the turn of the century and many papers and books attest to the time and resources spent optimizing these processes. Natural systems for wastewater treatment are still in their infancy by comparison and need new approaches and new tools from the engineering and science disciplines to fully develop their potential.

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TECHNOLOGIES FOR THE REMOVAL OF ARSENIC FROM DRINKING WATER IN NEW MEXICO

J. Bates[93], A. Hanson[94], F. Cadena[95], B. Thomson[96],
M. Johnson[97], D. Heil[98], and A. Bristol[99]

ABSTRACT

The U.S. Environmental Protection Agency (EPA) is proposing changes to the Safe Drinking Water Act (SDWA) which will drastically reduce the level of arsenic allowed in public water supplies. This regulatory change will have a dramatic impact on the arid southwestern states. Unfortunately, there are very few low tech, inexpensive ways to remove this contaminant. The traditional treatment technologies are reverse osmosis, and coagulation/flocculation. Both of these will be expensive, one because of the technology, the other because of the tankage involved. Ion exchange is a fully developed alternative technology which is well understood. Unfortunately, the high sulfate waters in New Mexico reduce the usefulness of ion exchange. Innovative technologies which are being considered include membrane processes and specialty filters. Membrane processes include; nanofiltration, ultrafiltration, and microfiltration with a coagulant. Activated alumina filters and oxidizing filters are both being proposed as appropriate technologies for smaller communities, but neither technology is fully developed.

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[93] NMSU/Civil, NMSU/Civil, Agricultural, and Geological Engineering
[94] NMSU/Civil, NMSU/Civil, Agricultural, and Geological Engineering
[95] NMSU/Civil, NMSU/Civil, Agricultural, and Geological Engineering
[96] UNM/Civil Engineering
[97] NMSU/Chemistry Dept.
[98] CSU/ Soil Chemistry
[99] NMSU/Soil Water and Air Testing Laboratory

PROBLEM IDENTIFICATION

How widespread is the problem? Arsenic concentrations in groundwater and surface waters can vary widely, with the most elevated concentrations on the order of tens of mg/L, while average concentrations are in the range of 2 to 5 µg/L (Herring and Chiu, 1998). Based on a number of recent surveys EPA (Reid, 1994) estimates the following relationship between the maximum contaminant level (MCL) set and the number of systems effected:

MCL Adopted (µg/L)	Number of systems impacted nationally (69,491 total)	Percentage of systems impacted
20	745	1%
5	4,921	7%
2	12,440	18%

New Mexico is likely to be disproportionately impacted by a new arsenic standard for two reasons: 1) over 90% of the states potable water sources are groundwater, and 2) the state has experienced extensive volcanic activity which often has high concentrations of arsenic (As) associated with it. The New Mexico Environment Department (NMED) has generated the following numbers for the state.

MCL Adopted (µg/L)	Percentage of systems impacted
20	4.4%
10	15.3%
2	50.8%

It is apparent that New Mexico, and most certainly the other arid southwestern states, bear a disproportionate burden in attempting to comply with the proposed arsenic regulation.

Arsenic has been recognized as a poison for nearly 4,000 years. The lethal effects are well documented, but the toxicity of As to humans at very low dosages is still not well understood. Some issues to be resolved include: is arsenic a micro nutrient, is there a threshold effect, does the human body metabolize arsenic? EPA has concluded that arsenic is carcinogenic, and therefore the desirable MCL is zero. However, the analytical means to measure arsenic at low levels is not available. Under this scenario, EPA sets the limit MCL at the practical quantitative limit (PQL), and then has the option of lowering the MCL as quantitative methods improve. The Canadian government recently decreased the maximum acceptable concentration (MAC) to 25 µg/L. EPA is currently considering arsenic MCLs in the range of 2 to 20 µg/L. EPA has recently initiated a major study of the toxicology of As that is scheduled to be completed in 2002. This information is to be used in developing the new MCL. Again, in addition to the toxicity study, the MCL will be based on the PQL criteria. As quantitative methods improve, the MCL will probably become more restrictive. EPA sets limits based on a health risk criteria, and these risk-based limits are then modified by other considerations, such as ability to measure (PQL) and ability to treat (BAT). In the case of arsenic, the contaminant level associated with an acceptable risk level is lower than the proposed MCL, thus as the PQL becomes more sensitive we can expect to see the MCL become more restrictive.

The other issue of concern is high cost of and uncertain performance of As treatment technologies. A large fraction of the communities which would be affected by a new, more stringent MCL, are very small water utility systems. Furthermore, many of these systems rely upon groundwater for their water supply and therefore do not provide any water treatment at present. Implementation of a more stringent MCL would require these water utilities to implement treatment, which would likely be quite costly. Accordingly, the financial impact of the new standard will be greatest on small communities. The individual households in smaller communities will bear a much higher cost per household than the households in larger communities. The City of Albuquerque, NM has estimated that a MCL of 5 µg/L will cost $200 million in capital investment and $10 million/year in operating costs. The state s NMED estimated the statewide cost of compliance to be $187 million. Regardless of which estimate is more accurate, it is clear that there will be a large cost associated with regulatory compliance. The citizens in the small communities are also the citizens who can least afford the cost of protection.

SUMMARY OF THE SOLUTION CHEMISTRY OF ARSENIC

The chemistry of As is complicated because it may occur in four stable oxidation states depending on the environmental conditions, each of which may participate in acid-base reactions. Examples of species associated with different environmental conditions are summarized in Table 1.

Table 1. Summary of the principal arsenic species found in the environment, and the general environmental conditions under which they are stable

Environmental Conditions	**Name**	**Principal As Species**
Oxidizing Conditions	Arsenates	H_3AsO_4, $H_2AsO_4^-$, $HAsO_4^{2-}$, AsO_4^{3-}
	Arsenites	H_3AsO_3, $H_2AsO_3^-$
Reducing Conditions	Elemental Arsenic	$As_{(s)}$
	Common Arsenic Minerals	$As_2O_{3(s)}$ - Arsenolite $AsS_{(s)}$ - Realgar $As_2S_{3(s)}$ - Orpiment $FeAsS_{(s)}$-Arsenopyrite
Methanogenic Conditions	Methylated As Compounds	$CH_3AsO(OH)_2$ - Methylarsonic Acid $(CH_3)_2AsO(OH)$ - Dimethylarsinic Acid
	Arsines	H_3As, $H_2As(CH_3)$, $HAs(CH_3)_2$, $As(CH_3)_3$

In water As is almost always present in either the arsenate form (As(V)) or the arsenite form (As(III)) (NOTE: The Roman Numeral in parentheses indicates the oxidation state of the compound). Both classes of compounds are very soluble. It is frequently assumed that As(III) predominates in groundwater as subsurface environments are generally more reducing, however, surveys by McNeill and Edwards et al. (1997) and results of Clifford et al. (1998) show that As(V) often is the dominant species in groundwater supplies.

It is important to understand the difference in solution chemistry of As(V) and As(III) species as this greatly affects water and wastewater treatment options. Near neutral pH As(V) is present as ionized species H_2AsO_4- and $HAsO_4^{2-}$, whereas As(III) is present as uncharged H_3AsO_3. This difference has enormous significance as many treatment processes are able to achieve selective removal of ionic constituents, while removal of non-ionized compounds is almost always difficult. Treatment processes which are effective for As(V) but not As(III) include ion exchange, adsorption onto activated alumina or ferric hydroxide, precipitation processes, and membrane filtration.

In considering the behavior of As in solution it is also important to recognize that the As(V) molecule is similar to that of sulfate (SO_4^{2-}) in that both are anionic molecules dominated by the presence of four O atoms. This similarity carries over to their solution chemistry where both are very soluble anions. Thus, many treatment processes which remove As(V) are affected by high sulfate concentrations. The situation is further complicated by the fact that treatment processes are expected to treat As(V) at concentrations of 10^{-6} moles/L (75 µg/L) or lower in a solution containing sulfate at 10^{-3} moles/L (96 mg/L) or greater. Therefore, the treatment process must either be very selective for As(V), or it must be expected to remove large mass of sulfate in order to remove a small mass of As.

Potential Solutions

The following paragraphs will discuss the current status of the treatment technologies available for the removal of arsenic from drinking water. Particular emphasis will be placed on issues of importance in New Mexico.

Membrane technologies

Membrane technologies represent a variety of options for treating water including: microfiltration (MF), ultrafiltration(UF), nanofiltrations(NF), and hyperfiltration or reverse osmosis (RO). These processes represent four overlapping categories of increasing selectivity related to decreasing membrane pore size. Brandhuber and Amy (1998a) report on a large number of studies which indicate that membrane processes are suitable for the removal of arsenic from water. Membranes can selectively exclude As from passing through them by two mechanisms: 1) exclusion based on size, and 2) exclusion based on electrostatic repulsion of the As ion. Brandhuber and Amy (1998a) note that this is most fortuitous since most UF and NF membranes are negatively charged, and arsenic in natural waters tends to be in the anionic arsenate form.

Brandhuber and Amy (1998a) showed, at a laboratory scale, RO and NF would remove 95 to 99% of all As(V) present in the water. Unfortunately, only 20 to 90% of the As(III) was removed depending on the pore size of the membrane. Energy costs can be reduced and production can be increased if an NF membrane is selected and pre-oxidation is performed to insure that As(V) is being treated. One danger associated with pre-oxidation, is that many of the membranes are sensitive to strong oxidants. It is important to either tightly control oxidant dosage, or select an oxidant tolerant membrane. The UF membranes tested were unable to achieve necessary arsenic removal.

Ghurye, Clifford, and Tong (1998) are involved in a study evaluating the use of iron coagulation coupled with MF for the removal of arsenic from Albuquerque groundwater. The City of Albuquerque has 92 drinking water wells, with arsenic concentrations ranging from 0.3 to 45.9 µg/L. The MCL eventually selected by EPA will have a large impact on treatment costs; if a MCL of 25 µg/L is selected, 13 wells will be in violation; if a MCL of 2 µg/L is selected, 72 wells will be in violation. Because of the geographically dispersed nature of the water system in Albuquerque, iron coagulation in conjunction with a Memcor Self Cleaning Continuous Microfiltration system appeared potentially attractive, since the system is compact and fully automated. The field scale testing demonstrated a number of things:

1. the system is not sensitive to sulfate concentrations (71 and 177 mg/L)
2. elevated silica levels are detrimental to the process
3. with the ferric salt a minimum mixing contact time of 17 seconds is required prior to filtration or the filter fouled 2-3 minutes into the filtration cycle
4. As adsorption is nearly completed within 10 seconds and is complete by 50 seconds
5. a mixing intensity (G) of 144 sec^{-1} is adequate
6. membrane pore opening is important; 0.22 mm pore opening works well
7. increasing backwash interval from 18-29 minutes and flux from 1.0 to 1.4 gpm/ft^2 produces no adverse impacts on either arsenic removal or on transmembrane pressure
5. the system is pH sensitive; to achieve a treatment goal of mg/L, a ferric dose of 2.5 mg/L is sufficient at a pH of 6.4, but a dose of 8 mg/L is required without pH adjustment

The coagulation/microfiltration system proved very robust and performed well. This result was confirmed by Brandhuber and Amy (1998b), who noted that they also had excellent results with a coagulation/microfiltration system.

Ion Exchange

Anion exchange has been suggested as the "method of choice" for the removal of arsenic from drinking water (Clifford, 1995). If As is to be removed effectively by anion exchange, it must be in the +5 valence state. This will frequently require pre-oxidation. In New Mexico the main concerns regarding the use of ion exchange are: the large amounts of salt brine associated with regeneration of the resin, sulfate competition, total dissolved solids (TDS) interference, and disposal of the arsenic containing brine regenerant. Clifford et al. (1998) addresses each of these issues in a paper evaluating ion exchange with brine reuse. The paper is based on work done in evaluating treatment alternatives for Albuquerque. This work showed that a conventional sulfate selective type 2 modified porosity polystyrene resin (ASB-2) gave the longest run lengths to arsenic breakthrough. The functional group on this resin is a quaternary amine. The work by Clifford et al. (1998) further demonstrated that, if there is significant carbonate in the water, pH could be used as an indicator of bed exhaustion. When the effluent pH matches the influent pH, the media is exhausted. This characteristic provides a field parameter which is easily monitored for operational control and prevents arsenic peaking from being a major concern. Clifford et al. (1998) used the University of Houston/EPA Mobil Drinking Water Treatment Facility to treat waters with arsenic in the range of 20 to 40 μg/L and sulfates in the range of 70 to 100 mg/L. The water was successfully treated to less than 2μg/L. The system had:

empty bed contact time (ebct) of 1.5 min
30-40 inch deep resin bed
run lengths of 400 to 450 bed volumes (BV)
superficial regenerate velocity of 2 cm/min

Because the water consumption and waste generation associated with regenerating the resin are a serious concern, Clifford et al. (1998) investigated the reuse of regenerate. The brine was reused 26 times in this study with no loss of effectiveness. The chloride consumption was reduced by 50% and the volume of brine discharged was reduced by 90%. It was also possible, through ferric hydroxide coagulation/ filtration, to remove the arsenic from the brine and further increase the useful life of the brine. Ion exchange with brine recycle shows great promise; there are, however, concerns. Based on mathematical modeling, Clifford (1998) showed that arsenic removal run length is very sensitive to sulfate concentration. The modelling produced the following raw water sulfate concentration (mg/L) to Bed Volumes (BV) of water produced ratios: 50 mg/L:1200 BV, 100 mgxL:500 BV, 200 mg/L :400 BV, 300 mg/L:200 BV. He recommended that ion exchange not be seriously considered if sulfate concentrations exceeded 250 mg/L, and one would prefer concentrations less than 120 mg/L sulfate. Clifford (1998) also states, if anion exchange is to be used for arsenic removal, the TDS concentration should be less than 500 mg/ L. Unfortunately many waters in New Mexico have high sulfates and high TDS, thus this very simple inexpensive alternative has limited application for many of the small communities in New Mexico.

Activated Alumina

Activated alumina can be viewed as a specialty filter media which would replace sand in a rapid sand filter. It exchanges arsenic out of water in much the same way that anion exchange does, but the As is removed by a complexation mechanism. Because of the difference in mechanisms, the activated alumina is not sensitive to sulfate concentration or TDS. Activated alumina is a pH sensitive process. Recent work has shown that As could be removed for 100,000 BV at pH of 6.0, but at a pH of 8 only 10,000 BV could be treated. There appears to be a loss of initial capacity when the activated alumina is regenerated. This phenomena is not well understood.

There are a number of things about this technology which are attractive. Activated alumina looks very promising for arsenic removal, and it will do simultaneous fluoride removal which is attractive in

New Mexico where the two often appear together. The on-off operation which is typical of small systems, appears to extend the life of this media.

There are also some concerns. The manufacturer that traditionally supplied activated alumina to the drinking water industry no longer has activated alumina available. The current availability of large quantities of high quality activated alumina has yet to be demonstrated. It does appear that the currently marketed activated alumina works well. There are some unanswered questions regarding the physical handling of activated alumina in a municipal system. Placing the media in the filter appears to be critical. A freshly placed bed must be extensively backwashed the first time it is wetted, or it sets up like cement. The backwashing operation, which may take hours, removes the rock-flour from the media, and hydrates the media.

As more is known about this technology, it may become the clear technology of choice.

Coagulation with iron and aluminum salts

Coagulation with iron and aluminum salts has been proposed by a number of investigators, and it appears to work well (Edwards, 1994, McNeill and Edwards, 1995, Scott et al., 1995, McNeill and Edwards, 1997). However, it also requires a treatment plant having a large number of treatment units (coagulation/flocculation/settling/filtration) with a treatment plant detention time of approximately 9 to 10 hours. Co-removal of arsenic during oxidation of Fe-Mn has also been suggested for the removal of As from drinking water (Edwards, 1994, McNeill and Edwards, 1995). Again, this technology appears to be very successful, but requires a number of treatment units. A minimum plant would include: aerator, curing tank, filters. It may require settling and possibly coagulation/flocculation.

Batch experiments on As removal by ferric hydroxide coagulation indicate a high potential for success (Edwards, 1994). It is well known that the Fe-hydroxyl functional group which is present on the surface of $Fe(OH)_3$ solids has a high affinity for oxyanions, including arsenate. The adsorption of arsenate results from the formation of a surface complex on $Fe(OH)_3$ as represented by the following reaction:

$$=Fe\text{-}OH + H_2AsO_4\text{-}\ \ V\ \ =Fe\text{-}H_2AsO_4 + H_2O$$

where the symbol =Fe represents an iron atom on a particle surface. Edwards (1994) reported that approximately 5 times more As was sorbed by ferric hydroxide precipitation when $Fe(Cl)_3$ and arsenate were added simultaneously as compared to adding arsenate to preformed or existing $Fe(OH)_3$ colloid particles. The increased removal of As was attributed to co-precipitation of Fe and As, with co-precipitation defined as the incorporation of As into a growing hydroxide phase. These observations are consistent with the result that the measured As removals were approximately 5 times greater than the amount of arsenate adsorption predicted by a diffuse-layer surface complexation model. Arsenate removal was greatest at pH of 7.0, and decreased as pH was increased to 9.0. The amount of arsenate removed was found to depend on the amount of Fe added, or the ferric coagulant dosage, and the lowest final arsenate concentrations were obtained when the ratio of Fe to As in the solid phase was 20:1 to 50:1. Greater than 95% removal of arsenate was achieved by ferric hydroxide coagulation in some cases.

Although ferric hydroxide coagulation was effective in removing arsenate, it was emphasized that the $Fe(OH)_3$ flocs that were formed were very stable in suspension, and filtration was required to separate the co-precipitated Fe-As solid phase.

Oxidizing filters

Oxidizing filters are used mainly for the removal of iron, manganese, and hydrogen sulfide. The term oxidizing filter is a broad one and refers to processes which oxidize soluble forms of metal species to insoluble forms either prior to or directly in the filter.

Some of the oxidants commonly used are:

® oxygen (air),
® chlorine (Cl_2),
® potassium permanganate ($KMnO_4$),
® ozone (O_3), or
® chlorine dioxide (ClO_2).

In most cases in oxidation filters, the oxidation is carried out at adsorption sites on the media with net result of considerable savings in the amount of retention time (i.e., tank volume) required.

Some materials can be used as oxidizing media by treating them with solutions of Mn(II) and permanganate. The treated material develops a coating of manganese dioxide which has a large adsorption capacity for both Fe(II) and Mn(II). Some common base materials are:

® natural zeolite (glauconite/manganese greensand)
® some forms of silica gel zeolite
® some forms of cation polystyrene resin
® pumicite
® and other materials, such as anthracite

Filter systems using any of these media types are commonly referred to as oxidizing catalyst filters.

Although the oxidation of As(III) by oxygen is slow, As(III) is readily oxidized by manganese oxide surfaces (Herring and Chiu, 1998). Similar oxidation of As(III) by amorphous ferric oxyhydroxides has been proposed, but does not occur in a time frame of a few hours (Herring and Chiu, 1998). As(III) is also not oxidized by crystalline iron oxides (Scott and Morgan, 1995) The effectiveness of arsenate removal during the oxidation of Fe(II) to Fe (III) should be similar to that observed for removal by ferric hydroxide coagulation via addition of $Fe(Cl)_3$, since in both cases the $Fe(OH)_3$ sorbent is produced. For example, the formation of 2 mg/L Fe solid precipitate should decrease soluble As concentration from 10 ppb to 0.75 ppb, based on predictions from adsorption modeling (Edwards, 1994). If co-precipitation is operative as well, even greater As removal should be obtained. The ferric hydroxide precipitate was also predicted to be much more effective than Mn oxide precipitate in the removal of arsenate.

Thus an iron oxide coated filter is appropriate for removal of As(V), and a manganese dioxide coated filter media is appropriate for oxidation of As(III) to As(V) and removal of the As(V). McMullin et al. (1998) report on a pressure filter using an iron oxide based media which is capable of treating water spiked with 200 µg/L to 2 µg/L for 4500 bed volumes. This media works well over a pH range of 6 to 8, but it is actually optimized at a pH of 5.5. Since this media is insensitive to either sulfate concentration up to 250 mg/L or chloride concentration, it appears that the media is forming surface complexes with the As and not undergoing ion exchange. A laboratory created iron coated sand has been shown in bench scale tests to be effective in removing As(V) from low pH waters (Benjamin et al., 1996). Unfortunately, there have been difficulties regenerating the media. A manganese dioxide coated media is capable of arsenic and iron adsorption with subsequent oxidation on the surface of manganese dioxide media. There is anecdotal evidence that this process may also be successful for the co-removal of As. A manganese greensand filter run in continuous regeneration mode removed 86% of the As in the water (Fonte, M, 1982). Edwards (1994) reports on a study in which 89 % of the As present was removed using a greensand filter. The water treated had 59 µg/L As (V), 2.9 mg/L Fe (II), and 0.47 mg/L Mn (II). No pH data was reported and no attempt was made to manipulate Fe-As ratios. Given the success of Fe-Mn oxidation in a conventional plant it is reasonable that the manganese dioxide filters could be optimized for removal of arsenic if Fe(II) is being removed.

In some cases the filter media is simply "aged." Aging refers to the practice of exposing the filter media to the raw water for a period of time, which allows a thin coating of oxide to accumulate on the media. The thin coating of oxide provides active adsorption sites. Aged media is most often used to remove Fe(II) and Mn(II). In these cases, ferric oxide and manganese dioxide are the respective precipitates, and it is noted that these materials have high sorption capacities for the reduced species Fe(II) and Mn(II), respectively.

Point of Use

Reverse osmosis is commonly used to remove arsenic from water in point of entry/point of use (POE/POU) applications. This technology requires some sophistication of the operator and the membranes have a limited life.

The Village of San Ysidro, NM, provides a good case study of the problems facing rural community water systems. The Village, located 70 miles northwest of Albuquerque along the southern flank of the Jemez Mountains, has a community water system that relies upon shallow groundwater resources which are plagued with problems of very poor quality water due to high concentrations of As (average concentration about 170 µg/L) and F (average concentration about 2.5 mg/L). The Village is very poor and cannot afford a conventional water treatment system. The water system was upgraded in 1987 at which time individual on-site water treatment devices were installed in each of the residences and commercial establishments. These under-the-sink point-of-use (POU) treatment systems provide filtration, activated carbon adsorption, and reverse osmosis treatment of up to 10 gallons/day of water which is used for direct human consumption. A monthly charge of $7 was added to each residential water bill to cover the costs of maintaining these systems by Village staff.

A study was conducted to evaluate the performance of the POU treatment systems in San Ysidro (Thomson and O'Grady, 1998). It was found that POU systems can provide a very high degree of treatment, including producing water with an As concentration of less than 10 g/L, provided they are properly maintained. However, it was also found that the overall performance of these systems has degraded due principally to inadequate maintenance. The POU system operation and maintenance programs were found to be strongly dependent upon the organization, technical abilities, and diligence of the water utility staff. The following recommendations were presented: 1) establish an adequate funding mechanism specifically dedicated to operation and maintenance of POU treatment units in the community; 2) develop a reliable system for tracking operation and maintenance activities for all POU treatment units in the community; 3) provide operator training and equipment for measuring the performance of POU systems; and 4) provide appropriate operator training and equipment for maintaining POU treatment systems. This study concluded that POU systems are an effective alternative to conventional centralized water treatment systems, but that a high degree of regular attention to each customer's POU system is required by water utility personnel.

CONCLUSION

Clearly, the new drinking water standards for arsenic being set by the USEPA pose a potential financial problem for many communities. There are a number of technologies which may be appropriate for use in rural New Mexico, but most appear to require a very sophisticated operator. An operator with a reasonable level of sophistication, will be an expensive employee, if one can be found to hire. There are no easy answers to this problem. The technologies exist to solve the problem of treating our waters to acceptable levels, but do the funds exist to pay for the treatment?

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GROUNDWATER TREATMENT BY CASCADE AIR-STRIPPING PROCESS

N. Nirmalakhandan, R. Brennan, and C. Trevizo[100]

ABSTRACT

Several drinking water supplies in the industrialized countries around the world are known to be contaminated with synthetic organic chemicals. The best available technologies for wellhead treatment of such waters are: counter current air-stripping and activated carbon adsorption. The former is well suited for volatile organic contaminants and a simple and cost-effective technology. Activated carbon adsorption while applicable to both volatile and semi-volatile chemicals, is at least 30% more expensive. Water utilities, remediation engineers, and researchers are therefore interested in improving the cost effectiveness of the air-stripping process and extending its applicability to a wider range of contaminants. In order to achieve these goals, theoretical considerations indicate that the air flow rate through the system has to be maximized. However, increasing the air flow rate beyond certain limits leads to prohibitive energy requirements and to process failure due to flooding. In this paper, a novel modification of the air-stripping process is described that has the potential to remove low and semi volatile organic contaminants cost effectively. Results of pilot, prototype, and field scale tests are presented to demonstrate the advantages of the proposed process. The cost effectiveness of the process even with off-gas treatment added is also demonstrated.

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[100] Civil Engineering Dept., New Mexico State University, Box 30001, MSC 3CE, Las Cruces, NM 88003.

INTRODUCTION

The most common approach to contain and/or remediate contaminated aquifers is to extract the groundwater and treat it at the surface (EPA/540/2-89/054, 1989). This approach, otherwise known as the "pump and treat method," has been applied in remediating hazardous waste sites as well as in wellhead treatment for potable water supply. For example, through 1995, 93% of the 605 sites on the National Priority List (NPL) have used the pump and treat approach alone; an additional 6% of the sites used pump and treat along with other in-situ technologies (EPA/542-R-96-005A, 1997). The goal of many of these cleanups is to restore the aquifer to beneficial use. In some cases, the objective is to keep the contamination from spreading.

Contamination of aquifers by organic chemicals is more widespread and common than by other chemicals. Volatile organic chemicals (VOCs), the most frequently occurring contaminant type, are present at more than two-thirds of all Superfund, RCRA, and DOD sites; half of all DOE sites; and are the primary contaminants at leaking underground storage tank (LUST) sites. Semi-volatile organic chemicals (SVOCs) are found at 30 to 60% of all these sites. The above data are representative of the sites remaining to be remediated as of 1995: 547 Superfund sites; 3000 RCRA sites; 165,000 LUST sites; 8,336 DOD sites; 10,500 DOE sites; 29,000 State sites; and 700 Civilian Federal Agency sites, totalling over 217,000 in all. Of these sites, 70% have groundwater or soil and groundwater contamination.

The best available technologies (BATs) for treating large quantities of aquifers contaminated by organic chemicals are granular activated carbon (GAC) adsorption and air-stripping. Of the two, GAC is generally more expensive and is more effective for highly adsorbable chemicals. Air-stripping is a low cost technology, but is applicable only to volatile chemicals, of Henrys Constant (H) greater than 100 atm.

Since the resources available for remediating contaminated aquifers is severely limited, one logical approach to meet remediation goals would be to enhance, optimize, and upgrade the best available technologies.

A novel modification of the conventional air-stripping process has been introduced as "cascade air-stripping" to remove low and semi-volatile organic contaminants from drinking water sources more efficiently (Nirmalakhandan et al., 1990). This process configuration consists of a packed tower down which the contaminated water flows under gravity as in the conventional air-stripping process. The air stream, instead of being admitted at the bottom of the tower, is distributed along the depth of the packing via evenly spaced air inlet ports. As the contaminants are stripped from the water into the gas phase, the fresh air entering the packing through the air inlet ports dilutes the contaminated air stream, thus maintaining a larger driving force for mass transfer throughout the depth of the packing. Since all the air volume does not have to flow through the entire depth of the packing media, the pressure gradient is maintained low, thus enabling larger air flow rates to be used without flooding the system. The increased driving force and the lower pressure drop translate into higher removal efficiencies or lower packing depths and lower energy requirements.

The technical feasibility of the cascade air-stripping process in removing volatile and semi-volatile organic contaminants from drinking water supplies has been demonstrated in previous studies at pilot and prototype scale laboratory studies (Nirmalakhandan et al., 1990, 1991). In these studies, the conventional air-stripping process was compared against the cascade process on various contaminants under a range of operating conditions. Advantages of the cascade system over the conventional air-stripping system documented in these studies are summarized in this paper. Results of a field scale demonstration project are also included along with cost comparisons with BATs.

Pressure Drop

The major operating cost of air-stripping systems is in overcoming the gas phase pressure drop across the packing. Because of the step wise addition of air through the packing, the cascade system can be operated under lower gas phase pressure drops than the conventional system. To demonstrate this advantage, a packed column was compared under the conventional and cascade modes, at pilot and prototype scales. The pilot scale column was of diameter 0.3 m with 25 mm size Tripack polypropylene packing to a depth of 4.6 m while the corresponding parameters of the prototype column were 0.45 m, 50 mm, and 5.4 m, respectively. The air flow rates and the pressure drops in these tests were compared in the two modes under equal energy input to the gas phase. The results of these comparative runs are presented in Table I. It can be seen from this comparison that the cascade system can accommodate 35-50% more air flow at 25-35% lower pressure drops than the conventional system.

Removal Capability

The increased air flow and the larger driving force result in higher removal efficiencies in the cascade process. To demonstrate this, removal efficiencies of the two systems were compared with layered packing in a 0.45 m dia. column. Three alternate configurations were evaluated:

Configuration 1: 25 mm dia. Tripack packing in the bottom 3.1 m and 50 mm dia. Tripack packing in the top 2.3 m
Configuration 2: 25 mm dia. Tripack packing in the bottom 1.5 m and 50 mm dia. Tripack packing in the top 3.9 m
Configuration 3: 50 mm dia. Tripack packing in the full 5.4 m

The removal of a very low volatile contaminant, 1,2-dibromo-3-chloropropane (H = 7 atm) by the two systems was compared under equal energy input. The results summarized in Table II confirm the

TABLE I. Comparison of Pressure Drop

Mode	Water loading (m^3/min-m^2)	Air flow (m^3/min)	Energy (cm-m^3/min)	Air-Wat. ratio (vol/vol)	Press. drop (cm H_2O)
Pilot scale system					
Conventional	0.37	1.5	3	88	1.9
Cascade	0.37	2.2	3	130	1.3
Conventional	0.37	2.2	6	130	2.7
Cascade	0.37	2.9	6	175	2.0
Conventional	1.00	1.5	5	26	3.1
Cascade	1.00	2.2	5	39	2.1
Conventional	1.00	2.2	10	39	4.5
Cascade	1.00	2.9	10	52	3.4
Prototype scale system					
Conventional	0.45	8.5	140	150	16.5
Cascade	0.45	14.1	134	250	9.5
Conventional	0.45	19.8	505	350	25.5
Cascade	0.45	29.7	505	525	17.0
Conventional	0.90	28.3	736	250	26.0
Cascade	0.90	42.4	763	375	18.0
Conventional	0.90	39.6	1,544	350	39.0
Cascade	0.90	59.4	1,544	575	26.0

superior performance of the cascade system: higher air flow rates, lower pressure drops, and higher removal efficiencies.

TABLE II. Comparison of Removal of 1,2-Dibromo-3-chloropropane

Mode	Air flow (m^3/min)	Press. drop (cm H_2O)	Energy (cm-m^3/min)	Air-Wat. ratio (vol/vol)	Removal (%)
Configuration 1					
Conventional	19.8	28.7	568	17	93.2
Cascade	26.6	21.1	561	23	97.6
Configuration 2					
Conventional	22.4	25.1	563	19	90.5
Cascade	30.8	18.3	563	26	97.4
Configuration 3					
Conventional	25.2	22.6	570	21	89.2
Cascade	36.4	15.7	573	31	96.2

Packing Depth Requirement

The capital cost of air-stripping systems is directly proportional to the packing volume. To compare the proposed process against the conventional process, optimized designs under various scenarios were generated using computer models that were validated in our previous studies (Nirmalakhandan et al., 1987). The packing volumes required by the two systems were compared for a range of removal efficiencies at different water flow rates and were estimated for five chemicals ranging from low to high volatility. These simulations showed a consistent trend of reduced packing volumes for the cascade air-stripping process. Results of typical runs at 95% removal efficiency and at two different water flow rates (13 and 26 m^3/min) are presented in Fig. 1 for five chemicals: chloroform (H = 140 atm); 1,1,1-trichloroethane (H = 230 atm); benzene (H = 250 atm); trichloroethylene (H = 475 atm); and tetrachloroethylene (H = 600 atm).

To confirm the above findings, removal efficiencies of a low volatile contaminant, bromoform (H = 35 atm), were measured for the two systems at equal energy input, but at 40% lower packing depth in the cascade system. Three of these comparisons were done at pilot scale, one at prototype scale. From the results of this study summarized in Table III, the cascade system can be seen to outperform the conventional system, with lower capital costs for a given operating cost or with lower capital and operating costs for a desired removal efficiency.

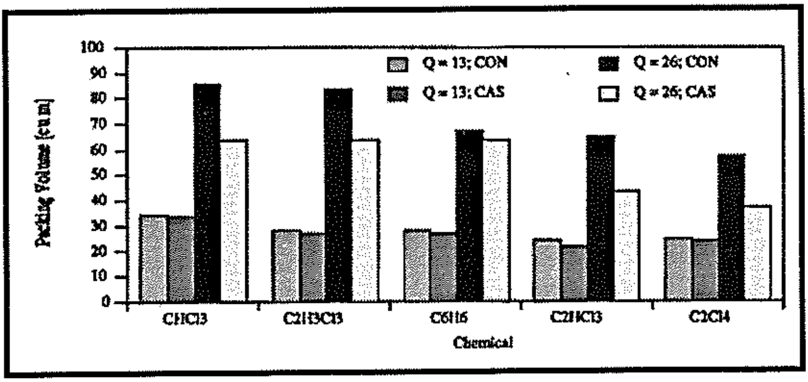

FIGURE 1. Comparison of Packing Volume required for 95% Removal of Five Chemicals:
CHCl3 - Chloroform; C2HCl3 - 1,1,1-Trichloroethane; C6H6 - Benzene;
C2HCl3 - Trichloroethylene; C2Cl4 - Tetrachloroethylene
Q - water flow rate treated in m3/min;
CON - conventional air-stripping; CAS - cascade air-stripping

TABLE III. Comparison of Depths

Mode	Depth (m)	Air flow (m^3/min)	Press. drop (cm H_2O)	Energy (cm-m^3/min)	Air-Wat. ratio (vol/vol)	Removal (%)
Pilot Scale System:						
Conventional	4.6	0.8	0.6	0.45	39	79.1
Cascade	2.7	1.5	0.3	0.45	78	84.7
Conventional	4.6	1.5	1.7	2.50	78	87.7
Cascade	2.7	2.9	0.8	2.32	154	91.4
Conventional	4.6	1.7	2.0	3.48	92	91.1
Cascade	2.7	3.5	1.0	3.48	184	92.8
Prototype Scale System:						
Conventional	5.4	10.0	17.0	170.00	93	80.3
Cascade	3.8	17.0	10.5	178.50	150	86.5

Field Results

To document the performance of the cascade process under field conditions, a prototype scale study was conducted at a major government facility. The target contaminant at this facility was trichloroethylene (TCE, H = 475 atm). A cascade air-stripping system was designed to treat groundwater at a rate of 48 m^3/hr with TCE concentration of 430 ppb. The design effluent concentration was 5 ppb, the US EPA's drinking water standard for TCE. Other contaminants at the site included tetrachloroethylene at 24 ppb; Freon-11 at 340 ppb; and Freon 112 at 1600 ppb.

The system exceeded the target removal efficiency of 98.8% for TCE and more than 99% for all the other contaminants. The system was evaluated at water flow rates ranging from 20 to 65 m^3/hr. Removals of TCE remained over 96% throughout these tests. The TCE-removal performance of the system at 64 m^3/hr monitored over 4 days is illustrated in Figure 2. All the other contaminants were removed to below 1 ppb level.

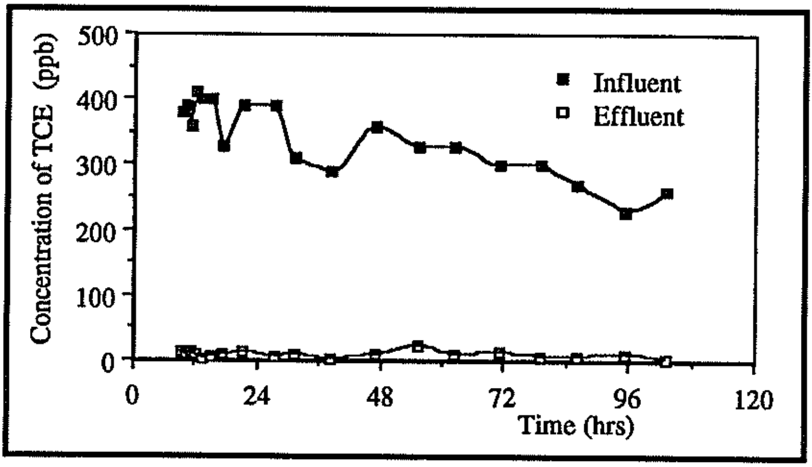

FIGURE 2. Field Results at 64 m3/hr- Cascade Air-stripping System

Cost Comparisons

When off-gas treatment is mandated, the cost-effectiveness of the cascade system may be impaired because the larger air flow rates result in proportionately higher off-gas treatment costs. The cost-effectiveness of the cascade air-stripping process with off-gas treatment added is evaluated in this study by comparing the following processes: liquid phase activated carbon adsorption process; conventional air-stripping process with off-gas treatment; and the cascade air-stripping process with off-gas treatment. This comparison is done for five common groundwater contaminants ranging in volatility from very low to medium, under various water flow rates ranging from 2 to 130 m^3/min.

The following five chemicals were selected for comparison: xylene (H = 345 atm); chlorobenzene (H = 265 atm); 1,2-dichloropropane (H = 162 atm); ethylene dibromide (H = 37 atm); and 1,2-dibromo-3-chloropropane (H = 7 atm). The cost of treatment by liquid phase activated carbon adsorption for these five chemicals at the different water flow rates reported by Adams et al. (1989) is used in this study. The costs of conventional air-stripping and cascade air-stripping for the same five chemicals have been reported by us previously (Nirmalakhandan et al., 1992). The off-gas treatment costs for the five chemicals under conventional air-stripping and cascade air-stripping were estimated in this study following the procedures recommended by the U.S. Environmental Protection Agency (US EPA, EPA/625/6-91/014, 1991).

The results of the comparison of overall treatment costs (¢/liter) by the three processes at various water flow rates are shown in figures 3 to 7 for the five chemicals. These evaluations confirm that the cascade system can be cost-effective even with off-gas treatment costs added on. Previous cost comparisons without including any off-gas treatment had indicated significant cost advantage for the cascade system (Nirmalakhandan et al., 1992). However, with off-gas treatment added, the advantage is somewhat offset due to the higher air flow rates in the cascade system.

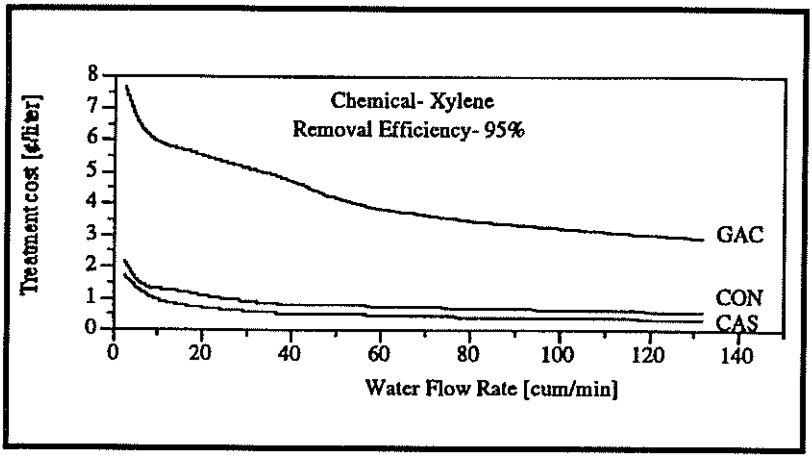

FIGURE 3. Treatment Cost at Various Water Flow Rates for Xylene
GAC- Liquid phase granular activated carbon treatment
CON- Conventional air-stripping with off-gas treatment;
CAS- Cascade air-stripping with off-gas treatment

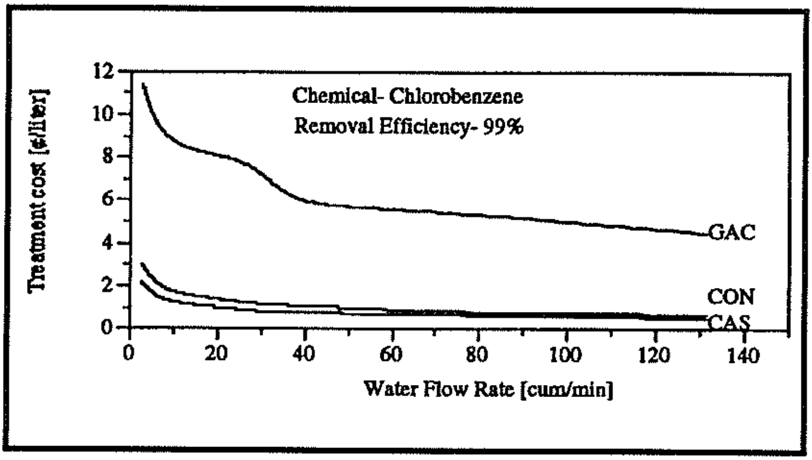

FIGURE 4. Treatment Cost at Various Water Flow Rates for Chlorobenzene
GAC- Liquid phase granular activated carbon treatment
CON- Conventional air-stripping with off-gas treatment;
CAS- Cascade air-stripping with off-gas treatment

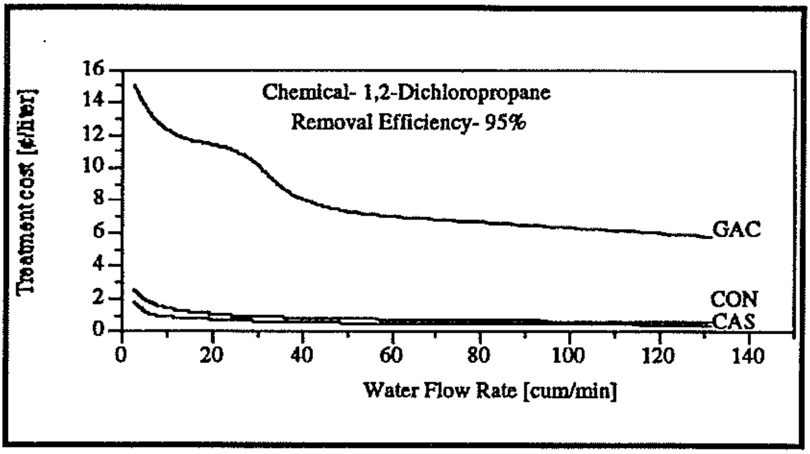

FIGURE 5. Treatment Cost at Various Water Flow Rates for 1,2-Dichloropropane

GAC- Liquid phase granular activated carbon treatment
CON- Conventional air-stripping with off-gas treatment
CAS- Cascade air-stripping with off-gas treatment

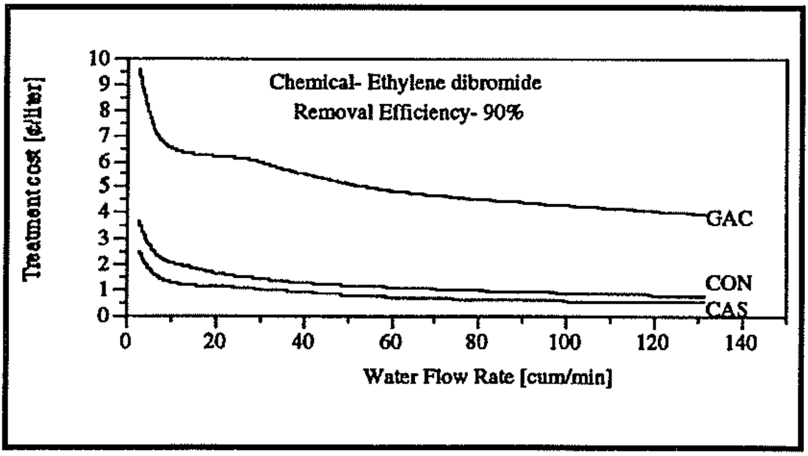

FIGURE 6. Treatment Cost at Various Water Flow Rates for Ethylene dibromide

GAC- Liquid phase granular activated carbon treatment
CON- Conventional air-stripping with off-gas treatment
CAS- Cascade air-stripping with off-gas treatment

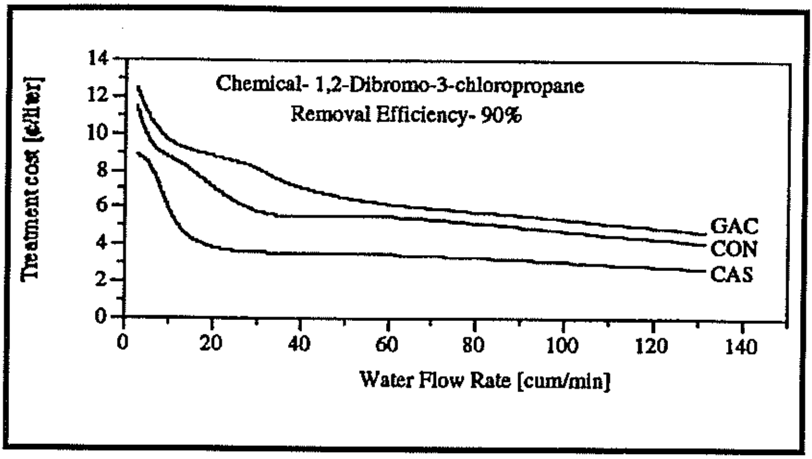

FIGURE 7. Treatment Cost at Various Water Flow Rates for 1,2-Dibromo-3-chloropropane

GAC- Liquid phase granular activated carbon treatment
CON- Conventional air-stripping with off-gas treatment
CAS- Cascade air-stripping with off-gas treatment.

CONCLUSIONS

Results of performance evaluations and the economic considerations suggest that the cascade air-stripping process may be an economically attractive alternative to treat drinking water sources contaminated with semi– and low–volatile organic contaminants. The pilot, prototype, and field scale test results indicate that the cascade process can accommodate 35 to 50% more air flow at nearly 40% less pressure drop, and achieve higher removal efficiencies than the conventional air- stripping process. The cascade system has been demonstrated to meet Regulatory Standards for drinking water in an energy-efficient, cost-effective, and environment-friendly manner.

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